

APPENDIX C

Equipment Specifications and Vendor Data

Emissions Data from Solar Turbines for Centaur 50-6200LS

Solar Turbines

A Caterpillar Company

PREDICTED EMISSION PERFORMANCE

Customer	
Job ID	
Inquiry Number	
Run By Brian K Maul	Date Run 13-Nov-07

Engine Model CENTAUR 50-6200LS CS/MD 59F MATCH	
Fuel Type SD NATURAL GAS	Water Injection NO
Engine Emissions Data REV. 0.1	

NOx EMISSIONS

CO EMISSIONS

UHC EMISSIONS

1	6703 Hp	100.0% Load	Elev.	200 ft	Rel. Humidity	60.0%	Temperature	0 Deg. F
PPMvd at 15% O2			25.00		50.00		25.00	
ton/yr			23.95		29.16		8.35	
lbm/MMBtu (Fuel LHV)			0.100		0.122		0.035	
lbm/(MW-hr)			1.09		1.33		0.38	
(gas turbine shaft pwr)								
lbm/hr			5.47		6.66		1.91	

2	6346 Hp	100.0% Load	Elev.	200 ft	Rel. Humidity	60.0%	Temperature	40.0 Deg. F
PPMvd at 15% O2			25.00		50.00		25.00	
ton/yr			22.87		27.85		7.98	
lbm/MMBtu (Fuel LHV)			0.100		0.122		0.035	
lbm/(MW-hr)			1.10		1.34		0.38	
(gas turbine shaft pwr)								
lbm/hr			5.22		6.36		1.82	

3	5027 Hp	75.0% Load	Elev.	200 ft	Rel. Humidity	60.0%	Temperature	0 Deg. F
PPMvd at 15% O2			25.00		50.00		25.00	
ton/yr			20.70		25.20		7.22	
lbm/MMBtu (Fuel LHV)			0.100		0.122		0.035	
lbm/(MW-hr)			1.26		1.53		0.44	
(gas turbine shaft pwr)								
lbm/hr			4.73		5.75		1.65	

Notes

- For short-term emission limits such as lbs/hr., Solar recommends using "worst case" anticipated operating conditions specific to the application and the site conditions. Worst case for one pollutant is not necessarily the same for another.
- Solar's typical SoLoNOx warranty, for ppm values, is available for greater than 0 deg F, and between 50% and 100% load for gas fuel, and between 65% and 100% load for liquid fuel (except for the Centaur 40). An emission warranty for non-SoLoNOx equipment is available for greater than 0 deg F and between 80% and 100% load.
- Fuel must meet Solar standard fuel specification ES 9-98. Emissions are based on the attached fuel composition, or, San Diego natural gas or equivalent.
- If needed, Solar can provide Product Information Letters to address turbine operation outside typical warranty ranges, as well as non-warranted emissions of SO2, PM10/2.5, VOC, and formaldehyde.
- Solar can provide factory testing in San Diego to ensure the actual unit(s) meet the above values within the tolerances quoted. Pricing and schedule impact will be provided upon request.
- Any emissions warranty is applicable only for steady-state conditions and does not apply during start-up, shut-down, malfunction, or transient event.

Solar Turbines

A Caterpillar Company

PREDICTED EMISSION PERFORMANCE

Customer	
Job ID	
Inquiry Number	
Run By Brian K Maul	Date Run 13-Nov-07

Engine Model CENTAUR 50-6200LS CS/MD 59F MATCH	
Fuel Type SD NATURAL GAS	Water Injection NO
Engine Emissions Data REV. 0.1	

NOx EMISSIONS

CO EMISSIONS

UHC EMISSIONS

4	4760 Hp	75.0% Load	Elev. 200 ft	Rel. Humidity 60.0%	Temperature 40.0 Deg. F
PPMvd at 15% O2	25.00	50.00	25.00		
ton/yr	19.19	23.37	6.69		
lbm/MMBtu (Fuel LHV)	0.100	0.122	0.035		
lbm/(MW-hr)	1.23	1.50	0.43		
(gas turbine shaft pwr) lbm/hr	4.38	5.33	1.53		

5	3351 Hp	50.0% Load	Elev. 200 ft	Rel. Humidity 60.0%	Temperature 0 Deg. F
PPMvd at 15% O2	25.00	50.00	25.00		
ton/yr	17.19	20.93	5.99		
lbm/MMBtu (Fuel LHV)	0.100	0.122	0.035		
lbm/(MW-hr)	1.57	1.91	0.55		
(gas turbine shaft pwr) lbm/hr	3.92	4.78	1.37		

6	3173 Hp	50.0% Load	Elev. 200 ft	Rel. Humidity 60.0%	Temperature 40.0 Deg. F
PPMvd at 15% O2	25.00	50.00	25.00		
ton/yr	16.01	19.50	5.58		
lbm/MMBtu (Fuel LHV)	0.100	0.122	0.035		
lbm/(MW-hr)	1.55	1.88	0.54		
(gas turbine shaft pwr) lbm/hr	3.66	4.45	1.27		

Notes

- For short-term emission limits such as lbs/hr., Solar recommends using "worst case" anticipated operating conditions specific to the application and the site conditions. Worst case for one pollutant is not necessarily the same for another.
- Solar's typical SoLoNOx warranty, for ppm values, is available for greater than 0 deg F, and between 50% and 100% load for gas fuel, and between 65% and 100% load for liquid fuel (except for the Centaur 40). An emission warranty for non-SoLoNOx equipment is available for greater than 0 deg F and between 80% and 100% load.
- Fuel must meet Solar standard fuel specification ES 9-98. Emissions are based on the attached fuel composition, or, San Diego natural gas or equivalent.
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- Any emissions warranty is applicable only for steady-state conditions and does not apply during start-up, shut-down, malfunction, or transient event.

Solar Turbines

A Caterpillar Company

PREDICTED ENGINE PERFORMANCE

Customer	
Job ID	
Run By Brian K Maul	Date Run 13-Nov-07
Engine Performance Code REV. 3.40	Engine Performance Data REV. 0.0

Model CENTAUR 50-6200LS
Package Type CS/MD
Match 59F MATCH
Fuel System GAS
Fuel Type SD NATURAL GAS

DATA FOR NOMINAL PERFORMANCE

Elevation	feet	200
Inlet Loss	in H2O	4.0
Exhaust Loss	in H2O	4.0
Accessory on GP Shaft	HP	14.0

		1	2	3	4	5	6
Engine Inlet Temperature	deg F	0	40.0	0	40.0	0	40.0
Relative Humidity	%	60.0	60.0	60.0	60.0	60.0	60.0
Driven Equipment Speed	RPM	13232	13291	12367	12250	11025	10539
Specified Load	HP	FULL	FULL	75.0%	75.0%	50.0%	50.0%
Net Output Power	HP	6703	6346	5027	4760	3351	3173
Fuel Flow	mmBtu/hr	54.56	52.23	47.19	43.86	39.23	36.63
Heat Rate	Btu/HP-hr	8141	8230	9388	9215	11707	11543
Therm Eff	%	31.256	30.918	27.102	27.610	21.735	22.043
Engine Exhaust Flow	lbm/hr	161294	150581	152958	139798	139444	1 6211
Exhaust Temperature	deg F	867	924	845	885	833	888

Fuel Gas Composition (Volume Percent)	Methane (CH4)	92.79
	Ethane (C2H6)	4.16
	Propane (C3H8)	0.84
	N-Butane (C4H10)	0.18
	N-Pentane (C5H12)	0.04
	Hexane (C6H14)	0.04
	Carbon Dioxide (CO2)	0.44
	Hydrogen Sulfide (H2S)	0.0001
	Nitrogen (N2)	1.51

Fuel Gas Properties	LHV (Btu/Scf)	939.2	Specific Gravity	0.5970	Wobbe Index at 60F	1215.6
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This performance was calculated with a basic inlet and exhaust system. Special equipment such as low noise silencers, special filters, heat recovery systems or cooling devices will affect engine performance. Performance shown is "Expected" performance at the pressure drops stated, not guaranteed.

Solar Product Information Letter 164
Description of SoLoNOx II

Solar Turbines

A Caterpillar Company

Product Information Letter

DATE: 11 December 2001
NUMBER: PIL 164
SUBJECT: **SoLoNOx II Low Emissions Systems**
AUTHOR: L.H. Cowell / K.O. Smith

INTRODUCTION

In 1992, Solar introduced the first industrial gas turbines employing a lean-premixed combustion system for emissions control. Since then, Solar has placed more than 750 SoLoNOx gas turbines into service. These turbines are routinely meeting emissions limits as strict as 25 ppmv NOx and 50 ppmv CO (15% O₂) on natural gas. Other gas turbine manufacturers have eventually followed suit and, at this time, nearly every manufacturer has introduced a low emissions gas turbine product line based on lean-premixed combustion.

Despite the significant improvements in gas turbine emissions since 1992, regulatory agencies continue to consider and implement more stringent emissions regulations. To meet the need for lower NOx, Solar has completed development work on the Centaur 50 and Taurus 60 engines and is now prepared to offer these models fired on natural gas as SoLoNOx II with 15 ppm NOx emission warranties.

PURPOSE

The purpose of this Product Information Letter (PIL) is to describe the unique features of SoLoNOx II. Also included are discussions of the changes to engine controls and operation, the design qualification completed, and the product experience gained to date.

SOLONOX II CAPABILITIES

SoLoNOx II is currently offered for gas Centaur 50 and Taurus 60 engines. In the future, reduced emissions capabilities will be offered on both gas and dual fuel Taurus 70, Mars and Titan engines. For Centaur 50 and Taurus 60 engines and packages, SoLoNOx II warranty and performance capabilities are:

- Emissions (NOx / CO / UHC ppm @15% O₂) – Natural Gas: 15 / 25 / 15
- Low Emissions Operating Range – Continuous compliance over the 50-to-100% load range of the engine with ambient temperatures above -20°C (0°F).
- Performance – Unchanged power and heat rate compared to SoLoNOx.
- RAMD – Reliability, availability, maintainability and durability levels expected to meet or exceed SoLoNOx.
- Exchangeability – SoLoNOx II engines are compatible with SoLoNOx packages with limited modifications.

Lean-Premixed Combustion

SoLoNOx and SoLoNOx II employ lean-premixed combustion to reduce NOx emissions. Lean-premixed combustion reduces the conversion of atmospheric nitrogen to NOx by reducing the combustor flame temperature. Since NOx formation rates are strongly dependent on flame temperature, lowering flame temperature (by lean operation) is an extremely effective strategy for reducing NOx emissions (Figure 1). Lean combustion is enhanced by premixing the fuel and combustor airflow upstream of the combustor primary zone. This premixing prevents stoichiometric burning locally within the flame, thus ensuring the entire flame is at a fuel lean condition.

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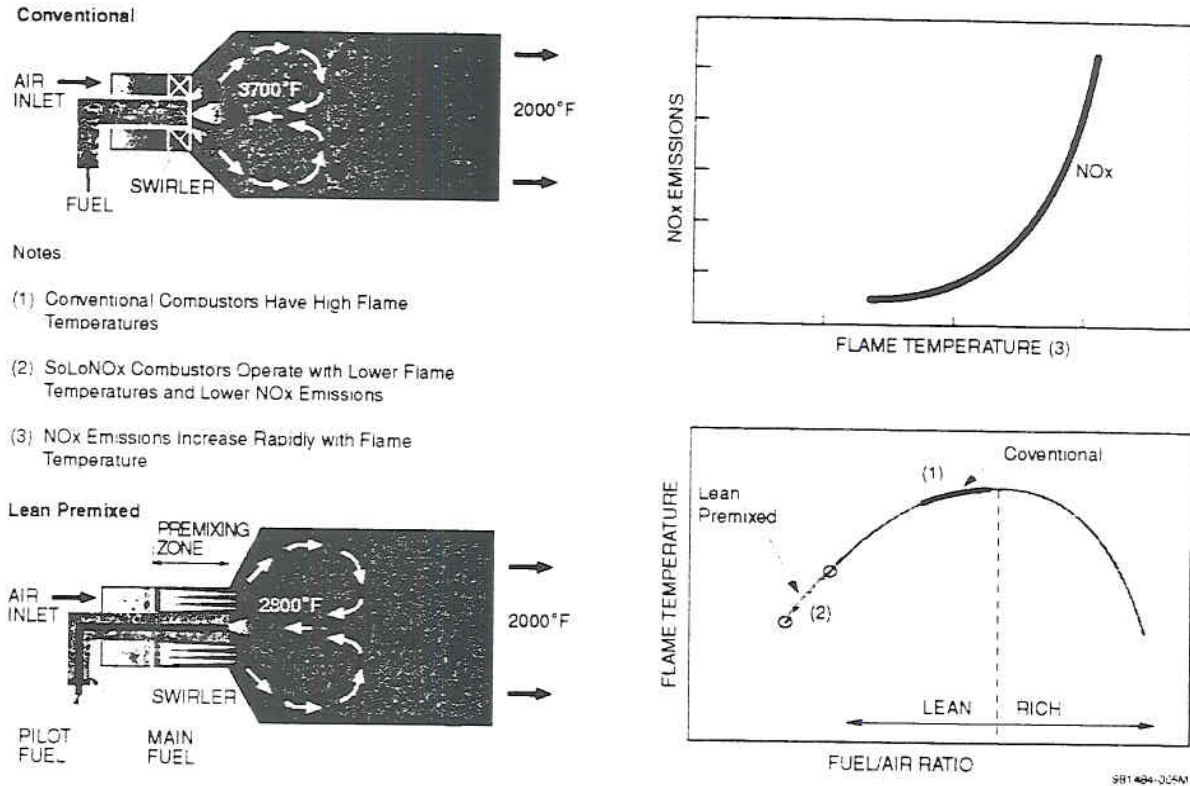


Figure 1. How Lean-Premixed Combustion Reduces NOx Emissions

There are two aspects of lean-premixed combustion that warrant attention:

- CO / NOx trade-off
- Combustor operating range

CO / NOx Trade-off

Since the flame temperature of a lean-premixed combustor is designed to be near the lean flammability limit, lean-premixed combustor performance is characterized by a CO / NOx trade-off (Figure 2). At the combustor design point, both CO and NOx are below target levels; however, deviations from the design point flame temperature cause emissions to increase. A reduction in temperature tends to increase CO emissions due to incomplete combustion; an increase in temperature will increase NOx. This trade-off must be addressed during part-load turbine operation when the combustor is required to run at an even leaner condition. The trade-off also comes into play in development efforts to reduce lean-premixed combustor NOx emissions by further reducing the primary zone design point temperature.

Combustor Operating Range

In a gas turbine, the lean-premixed CO / NOx trade-off is manifested as a limited load range over which emissions limits can be satisfied. As a gas turbine moves away from full-load operation, a lean-premixed combustor will eventually produce excessive CO emissions. To broaden the operating range, low emissions gas turbines can use combustor airflow control within the gas turbine to maintain a nearly constant flame temperature.

Combustor airflow control is achieved with compressor air bleed at part load to broaden the operating range of the lean-premixed combustion system for two-shaft engines. Single-shaft gas turbines use the inlet guide vanes (IGV) to perform the variable geometry function.

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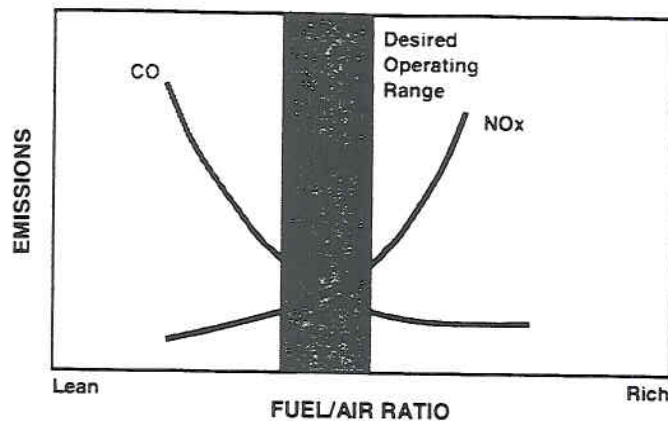


Figure 2. Typical Lean-Premixed Combustor Emissions

SOLONOX II DESIGN

The primary change from SoLoNOx to SoLoNOx II is to incorporate an **Augmented Backside Cooled (ABC)** combustor liner. SoLoNOx II also employs the latest fuel injector design and improvements to the fuel and controls systems. The following sections describe the ABC combustor and other changes made for SoLoNOx II.

Augmented Backside Cooled (ABC) Liners

The present generation of lean-premixed combustors primarily uses film cooling to maintain acceptably low combustor wall temperatures. Film cooling involves the passage of cooling air through holes in the liner and the formation of a cooling film on the hot side of the liner, using internally positioned louvers or effusion cooling as depicted in Figures 3 and 4.

Research has shown that the method used to cool a lean-premixed combustor liner can have a significant effect on emissions. Specifically, conventional film cooling can lead to reaction quenching at the combustor primary zone wall. This quenching process leads to high CO emissions because the CO, a combustion intermediate, is prevented from oxidizing to CO₂. The quenching is traceable to the injection of a relatively large flow of cooling air into the primary zone.

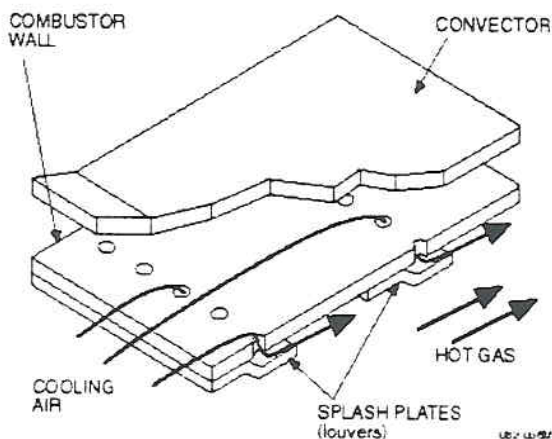


Figure 3. Louver Cooling Design

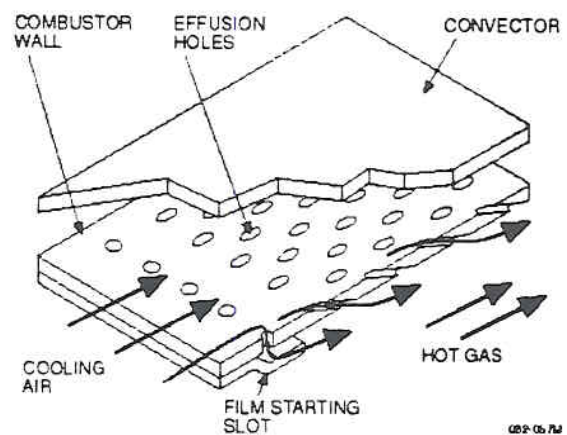


Figure 4. Effusion-Cooling Design

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The development of an advanced liner that does not promote reaction quenching provides a two-fold benefit in terms of emissions. First, of course, CO emissions are reduced. Additionally, the lower CO levels allow combustor reoptimization to a lower flame temperature. This produces lower NO_x levels along with the lower CO concentrations. Figure 5 shows graphically how the ABC liner reduces CO emissions and the corresponding optimum fuel/air ratio reduces NO_x emissions.

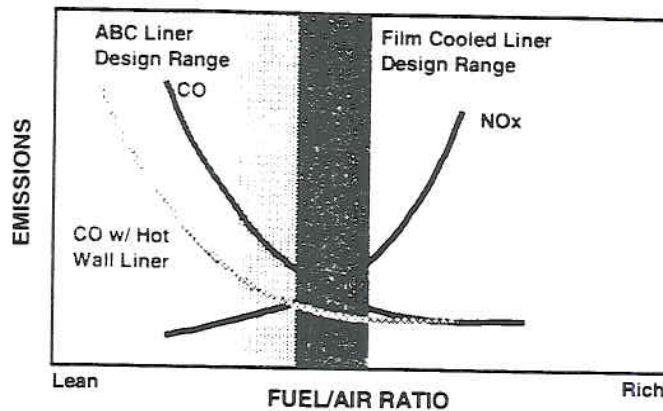


Figure 5. Extension of Design Range with ABC Combustor Liner for Low Emissions

ABC liners forego cooling air injection completely. Instead, combustor wall temperatures are controlled solely through convective cooling by a high velocity airstream on the cold side of the liner (Figure 6). In most instances, the high heat flux from the flame requires augmenting of the backside convective process to keep liner wall temperatures from becoming excessive. Turbulators in the form of trip strips, fins, and pins act to increase the cooling flow turbulence at the liner wall and augment the heat removal process.

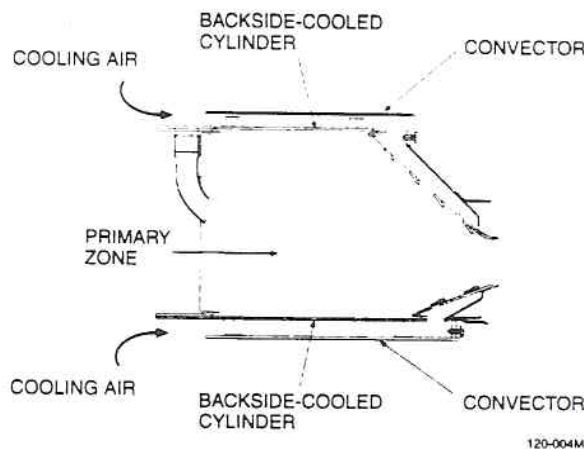


Figure 6. Augmented Backside-Cooled (ABC) Combustor Cross Section

Although effective in reducing CO formation through quenching, backside cooling is a challenge to implement because of the high flame temperatures and heat fluxes associated with gas turbine combustors. An additional degree of liner protection can be achieved through the application of a thermal barrier coating (TBC) on the hot sides of the liner walls. These TBCs are frequently composed of zirconia-based materials that are plasma-sprayed on the liner. A typical TBC coating of approximately 0.25 mm (0.01 in.) can reduce wall temperatures by approximately 40°C (72°F).

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The durability of the ABC liner is expected to meet or exceed durability demonstrated with film-cooled liners. Liner durability is determined by two factors: temperature and temperature gradient. Wall temperatures must be kept sufficiently low to prevent long-term oxidation or thermal creep. Solar's experience indicates that in most circumstances a wall temperature limit of 1600°F provides excellent life. This criterion is applied to the design of all gas turbine liners, including film-cooled diffusion flame and DLE film-cooled liners, as well as backside cooled liners.

Excessive thermal gradients along the liner wall can lead to high stress concentration gradients that cause buckling or cracking. Assessing liner thermal gradient limits requires a combination of thermal paint temperature analysis, stress analysis and operating experience. The thermal gradients in Solar's film-cooled liners have been determined to be acceptable for long liner life. Generally, the thermal gradients in ABC liners are lower than most film-cooled liners. Therefore, the corresponding life of ABC liners is expected to meet or exceed film-cooled liners.

Fuel Injectors

SoLoNOx II uses the latest version of fuel injectors from SoLoNOx. As can be seen in Figure 7, these injectors are significantly larger than the conventional combustion counterparts due to the higher airflow through the injector air swirlers and the required volume of the premixing chamber used to mix the fuel and air. The injector module includes a premixing main fuel injector and a pilot fuel injector.

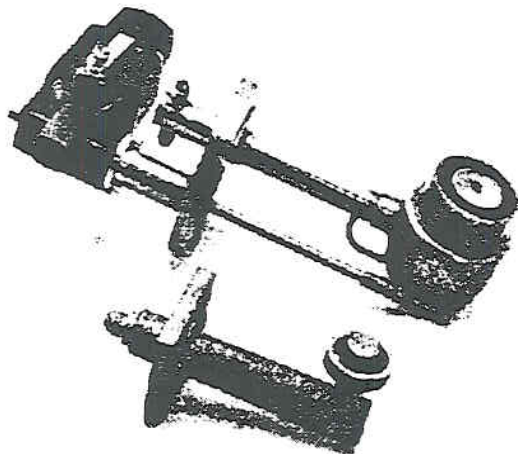


Figure 7. Comparison of SoLoNOx and Conventional Fuel Injectors

Main Fuel Circuit. The premixing main fuel injector uses an axial swirler to impart a high degree of swirl to the primary zone air. A series of multi-orificed, radial fuel tubes injects natural gas fuel into air just downstream of the air swirler. Uniform mixing of the fuel and air occurs within the annular premixing chamber prior to reaching the combustor primary zone. The strong swirl stabilizes the combustion process in the primary zone by establishing a recirculation zone that draws reacted hot gases back upstream, thus providing a continuous ignition source. Above 50% engine load, greater than 95% of the fuel is introduced through the main fuel tubes.

Pilot Fuel Circuit. The pilot fuel injector circuit is used mainly for lightoff and low-load operation. The pilot fuel injector consists of an air swirler and tangential fuel inlet ports to provide partial premixing of air and fuel prior to combustion. During lightoff and low-load operation, approximately 30 to 50% of the fuel passes through the pilot injector, providing a rich fuel / air mixture. Combustor stability is enhanced in this mode compared to lean-premixed operation, although NO_x and CO emissions are higher. Above 50% engine load, the pilot fuel is reduced to less than 5% of the total fuel flow to optimize emissions performance. The pilot fuel is also momentarily increased during off-load transients to help stabilize the flame during the transient.

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Combustor Air Management

The airflow to the SoLoNOx II combustor is controlled to avoid lean extinction and broaden the low emissions operating range in the same way as for SoLoNOx. Two techniques are used to control the primary zone airflow to maintain the primary zone fuel/air ratio near its optimum low emissions level during part-load engine operation. Two-shaft gas turbines used for gas compression and mechanical drives, bleed air from the combustor casing at part load. Single-shaft gas turbines used for power generation maintain optimum primary zone fuel/air ratios by modulating the compressor inlet guide vanes (IGV). Closing the IGVs reduces the airflow through the engine compressor and combustor.

Swirler Inlet Valve

Centaur 50S and Taurus 60S gas turbine fuel injectors have had a two-position swirler inlet valve (SIV) located upstream of the main air swirler, which was used to control the airflow into the combustor primary zone. The design intent was to offer additional low emissions combustor operating range without increasing the engine heat rate. However, in practice, the part-load heat rate reduction has been lower than anticipated. Therefore, with SoLoNOx II gas-only Centaur 50S and *Taurus* 60S gas turbines, the injector SIV has now been removed to reduce system complexity and cost and improve injector durability.

Engine Casings

SoLoNOx II gas turbines use the same engine casing as SoLoNOx.

Control System

SoLoNOx II and SoLoNOx engines utilize identical control philosophies, incorporating methods to improve control precision, accuracy and reliability. During start-up and low-load operation, the pilot flow rate has been optimized to achieve maximum flame stability for the most rapid and flexible transient capability. Below 50% load for gas fuel (80% for liquid fuel), the combustor airflow is managed in the same way as in a conventional engine. SoLoNOx and SoLoNOx II differ from conventional above 50% for gas (80% for liquid) of the rated load – the low emissions mode. The control system for SoLoNOx II engines modulates either the bleed valve or IGVs to keep the combustion primary zone temperature within a specified range. Accurate control of the primary zone temperature is critical to controlling NOx and CO emissions. SoLoNOx II requires highly accurate electric actuators on the system being modulated to control the primary zone temperature to ensure repeatable and accurate emissions control. The benefits of using electric actuators extends beyond emissions to other elements of engine performance and transient response. The SoLoNOx II gas turbine controls use the power turbine inlet temperature (T_5) as an indirect measurement of the primary zone temperature to control the bleed valve or IGV position as a function of engine load.

Fuel Systems

As with SoLoNOx, the natural gas fuel system for SoLoNOx II gas turbines includes two separate fuel circuits: one for the pilot system and one for the main system. Separate fuel manifolds are used to supply pilot and main gas to the respective fuel circuits of each fuel injector. The fuel flow split between main and pilot is controlled with a precision electronic valve on the pilot line. During start-up and low-load operation, high flow rates of pilot gas are used. When the engine is in the low emissions mode, the pilot fuel valve throttles the pilot valve to low levels. The low pilot flow is used to stabilize the flame.

QUALIFICATION AND EXPERIENCE

The primary improvement associated with SoLoNOx II is the incorporation of the ABC liner. Extensive qualification work was completed on the combustor liner in both rig and engine tests. The initial SoLoNOx II package was qualified in the factory and the field.

ABC Liner Development

Initial development work on the ABC combustor was directed at the Centaur 50 gas turbine in a joint Solar / U.S. Department of Energy program. A short in-house gas turbine test documented excellent emissions performance and acceptable wall temperatures at full-load conditions. A 50-hour cyclic test was completed to demonstrate thermal barrier coating (TBC) spalling resistance.

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A field test of a prototype Centaur 50 ABC combustor is ongoing. Testing of this liner was initiated in 1998 in a two-shaft Centaur 50S at a compressor station in Arizona. More than 18,000 hours of operation were achieved at that site. Site emissions were consistently less than 15 ppm NO_x and 25 ppm CO from 50 to 100% of rated engine load and ambient temperatures from the 40 to 110°F. In December 2000, the prototype liner was pulled from the engine and examined thoroughly. The liner was in excellent condition with no signs of TBC spalling or cracking and no indications of any premature wear. In early 2001, this same liner was installed in a single-shaft Centaur 50S used in a cogeneration application in Massachusetts. To date, the liner has accumulated an additional 4750 hours, bringing the total liner firing time to 22,750 hours. Emissions continue to be below 15 ppm NO_x at this cold weather plant (Figure 8) in both winter and summer. Although not indicated, the corresponding CO emissions are below 10 ppm at all engine loads.

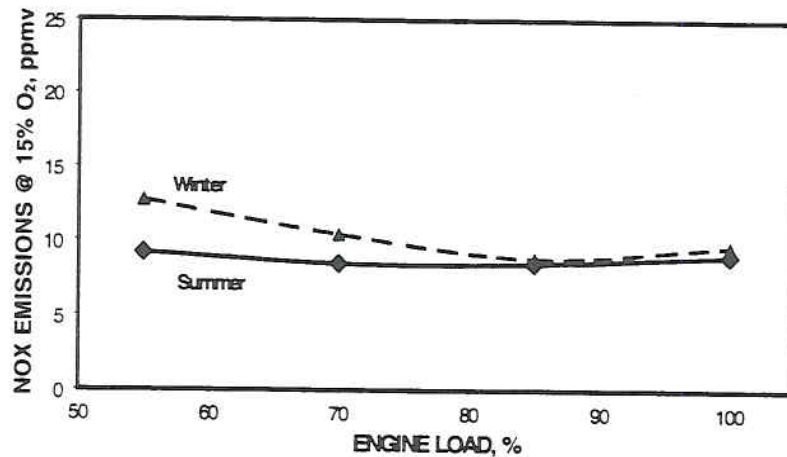


Figure 8. ABC Liner Emissions Performance in a Cogeneration Application in Massachusetts

Following the very successful demonstration of the prototype, the ABC liner design was made production ready. Additional rig and engine testing were completed to verify that the minor changes required for the production design did not impact durability or performance. The liner was tested to verify that the outlet temperature profile is suitable for turbine hot end life. An engine thermal paint test (Figure 9) was completed to assess maximum wall temperatures and thermal gradients. The paint colors and uniformity of thermal paint shading on the combustor liner in Figure 9 indicate acceptable temperatures and gradients. A detailed mechanical analysis was completed, indicating low stress levels and concentrations. The ABC liner is now in full production and successfully qualified for SoLoNO_x II.

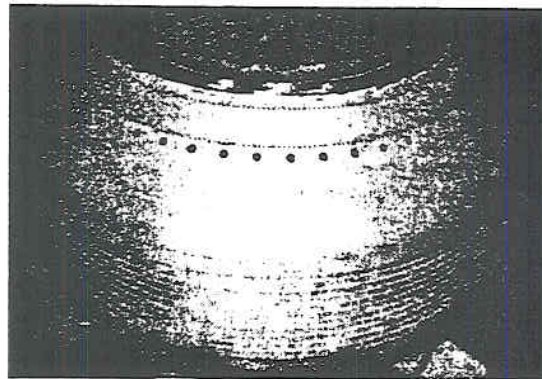


Figure 9. Thermal Paint Applied to an ABC Combustor Liner Indicating Acceptable Temperatures and Low Thermal Gradients

SoLoNOx II Experience

SoLoNOx II has been offered on a "demonstration" basis since mid-2000. Five gas Taurus 60S and one Centaur 50S turbine have been built, factory tested and shipped to site. Four of the Taurus 60S CED packages are in operation at one site in a cogeneration application in Texas. The other Taurus 60S and the Centaur 50S are two-shaft machines and will run in pipeline compressor applications.

Engine build and factory test for all six SoLoNOx II units were completed with no differences from SoLoNOx units except reduced NOx. Engine operation was not affected nor was power or heat rate. The transient ability to handle full off-loads and on-loads was consistent with similar SoLoNOx engines.

Figure 10 summarizes the factory emissions for these units, indicating the capability to meet 15-ppm emissions warranties with margin from 50 to 100% load. CO and unburned hydrocarbon emissions were below 10 ppm for all operating points indicated.

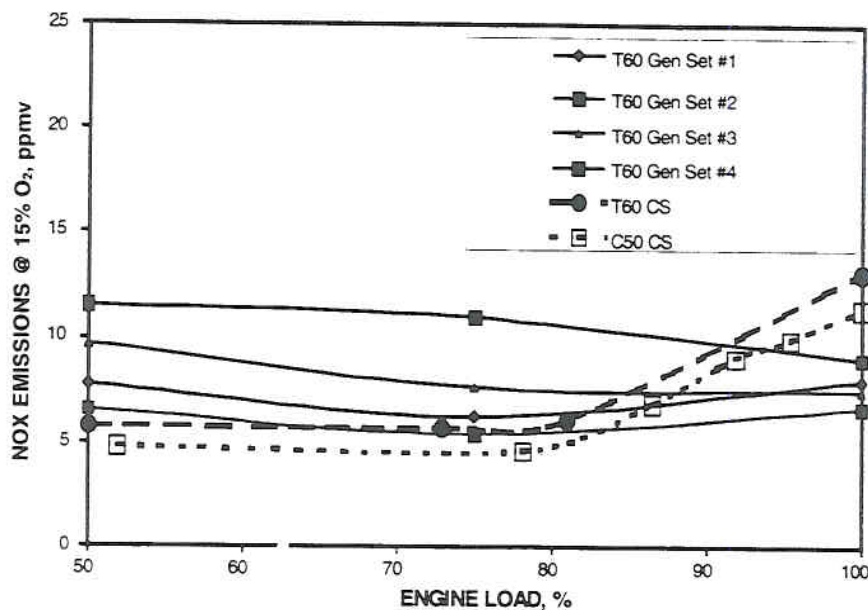


Figure 10. Factory Emissions Performance SoLoNOx II Demonstrator Units

Operation of SoLoNOx II in the field was initiated in June 2001 with the four Taurus 60S packages in Texas. These units were commissioned without difficulties and have been operating without issues, meeting 15 ppm NOx. The customer reports satisfaction with the units. The early hour operation of these units plus the 22,750 hours of engine time demonstrating ABC liner indicates that SoLoNOx II will be a product with excellent reliability, availability, maintainability, and durability (RAMD).

SUMMARY

SoLoNOx II is now being offered for gas-only Centaur 50S and Taurus 60S HED and CED engines and packages. SoLoNOx II emissions warranties can be offered as low as 15 ppm NOx and 25 ppm CO over an operating range of 50 to 100% load and ambient temperatures above 0°F. Development and qualification work continues to offer lower emissions for the Taurus 70, Mars and Titan engines and for all dual fuel SoLoNOx products.

At the heart of SoLoNOx II is a change in the combustor to an ABC liner configuration. Also included are improvements to the IGV and bleed valve actuators and fuel valves to improve precision, speed, and reliability. The improved actuators and fuel valves are now standard for all new shipments, but upgrades

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are necessary for existing package retrofits. There are no operational impacts or restrictions associated with SoLoNOx II.

The ABC liner has been extensively qualified, including more than 22,750 hours of engine operating time in the field. SoLoNOx II emission levels and performance have now been demonstrated on six production units. Four of these units are operating successfully in the field.

ACKNOWLEDGEMENTS

Design, development and production implementation of the Centaur 50 and Taurus 60 ABC combustor liner were completed by A. Batakis, A. Fahme, K. Maden, E. Metzdorf, D. Pessin, J. Powell, and P. Schneider.

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**Solar Product Information Letter 167
Emissions in Sub-Zero Ambient Conditions**

SoLoNOx Products – Emissions in Non-SoLoNOx Modes

Leslie Witherspoon
Solar Turbines Incorporated

PURPOSE

Solar's dry-low NOx emissions systems (SoLoNOx) have been developed to provide the lowest emissions possible during normal operating conditions. In order to optimize the performance of the turbine, the combustion and fuel systems are designed to reduce NOx, CO and unburned hydrocarbons (UHC) without penalizing stability or transient capabilities. At very low load and cold temperature extremes, the SoLoNOx system must be controlled differently in order to assure stable operation. These required adjustments to the engine controls at extreme conditions cause emissions to increase. Emission warranty limitations are, therefore, imposed for load (50 to 100%) and for cold ambient temperatures (>0°F).

The purpose of this PIL is to provide emissions estimates for NOx, CO and UHC at these off-design conditions.

COLD AMBIENT EMISSIONS ESTIMATES

Solar's standard temperature range warranty for SoLoNOx engines is >0°F. At ambient temperatures below 0°F, the unit is no longer in SoLoNOx mode and emissions are expected to be higher than when operating in SoLoNOx mode. At ambient temperatures below 0°F, many of Solar's tur-

bine engine models are controlled to increase pilot fuel from approximately 3 to 10% of the total fuel flow to improve flame stability. Without this increase in pilot fuel at temperatures below 0°F, the engines may exhibit combustor rumble since operation may be near the lean stability limit.

For permitting purposes, customers have used the New Source Performance Standard (NSPS) levels, 40 CFR 60, subpart GG for a conservative NOx emission estimate at ambient temperatures below 0 °F. Table 4 herein summarizes NSPS NOx emission levels for Solar's equipment.

In some cases, either the customer or regulatory agency desires a "less conservative" estimate of actual emissions for when the turbine is not operating in SoLoNOx mode. For such instances, the following actual emission estimates are provided. "Expected" emissions are extrapolated from San Diego factory tests and may vary at these extreme temperatures and as a result of variations in other parameters such as fuel composition, fuel quality, etc. Emission warranties cannot be offered for ambient temperatures below 0°F.

For **SoLoNOx engine models**, except for *Centaur 40* and *Mars 90*, expected emissions (ppm corrected to 15% O₂) as a function of ambient temperature are given in Table 1.

Table 1. Expected Emissions below 0°F (except for Centaur 40 and Mars 90)

Ambient	Fuel System	Fuel	NOx, ppm	CO, ppm	UHC, ppm
0°F to -20°F	Gas only (50 to 100% load)	Gas	42	100	50
	Dual fuel (80 to 100% load)	Gas	72	100	50
		Liquid	120	150	75
Below -20°F	Gas only (50 to 100% load)	Gas	120	150	75
		Gas	120	150	75
	Dual fuel (80 to 100% load)	Liquid	120	150	75

Table 4. NSPS Limits (NO_x, ppmv @ 15% O₂)

Product		Gas Fuel	Gas Fuel >1/3 Power to Grid	Liquid Fuel ^{a,b}	Liquid Fuel ^{a,b} >1/3 Power to Grid
Titan 130-19500	GSC	209 ^a	105 ^a	205	102
	CS/MD	214 ^a		210	
Mars 100-15000	GSC	209 ^c	105 ^a	207	104
	CS/MD	203 ^c		201	
Mars 90-13000	GSC	205 ^c		197	
	CS/MD	199 ^c		193	
Taurus 70-10300	GSC	212 ^a		210	
	CS/MD	207 ^a		201	
Taurus 60-7300, -7800	GSC	190 ^c /193 ^c		188/191	
	CS/MD	190 ^c /193 ^c		188/191	
Mercury 50	EXEMPT				
Centaur 50-6200, -6100	GSC	184 ^c		183	
	CS/MD	180 ^c		177	
Centaur 40-4700	GSC	182 ^c		179	
	CS/MD	167 ^c		165	
Saturn 20-1600	GSC	156 ^c		155	
	CS/MD	150 ^c		150	

^a SoLoNO_x, water injection, or add-on control is required to meet NSPS

^b Fuel bound nitrogen content assumed to be <0.015% by volume

^c Conventional turbine meets NSPS

mates of NO_x, CO, and UHC emissions when operating below 50% load and above -20°F. The estimated emissions can be assumed to vary linearly as load is decreased from just below 50% load to idle.

natural gas. At ambient temperatures below -20°F, the NO_x emission estimate is 120 ppmv for loads <50%. For liquid fuel operation below 80% load, emissions documentation is in progress.

The above values apply for any product for gas only or dual fuel systems using pipeline quality

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For ***Centaur 40*** and ***Mars 90*** engine models, expected emissions (ppm corrected to 15% O₂) as a function of ambient temperature are given in Table 2.

Some regulatory agencies in states with colder winter climates (primarily Alaska and Wyoming) have started to ask about cold ambient temperature restrictions and corresponding emissions below 0°F. In all cases to date, the regulatory agency did not require a certain emission level to be met, but merely asked what emissions are expected so that emissions could be appropriately estimated for annual emissions inventory purposes and NSR applicability issues.

Some customers have used the permitting strategy of installing digital thermometers to record ambient temperature. The amount of time is recorded that the ambient temperature falls below 0°F. The amount of time below 0°F is then used with the emission estimates shown above to estimate "actual" emissions.

For customers who wish to permit at a single emission rate over all temperatures, inlet air heating can be used to raise the engine inlet air temperature (T1) above 0°F. With inlet air heating to keep T1 above 0 °F, standard emission warranty levels may be offered.

EMISSIONS ESTIMATES AT LESS THAN 50% LOAD

At operating loads <50%, *SoLoNOx* engines are controlled to increase stability and transient response capability. The control steps that are required affect emissions in two ways: 1) pilot fuel flow is increased, increasing NO_x emissions, and 2) airflow through the combustor is increased, increasing CO emissions. Note that 50% load is an approximation and that engine controls are triggered either by power output for single-shaft engines or gas producer speed for two-shaft engines.

For permitting purposes, Solar has historically recommended the use of New Source Performance Standard (NSPS) levels, 40 CFR 60, subpart GG for conservative NO_x emission estimates outside the typical load range warranty. (Table 4 herein summarizes NSPS NO_x emission levels for Solar's equipment.)

In some cases, either the customer or regulatory agency desires a "less conservative" estimate of actual emissions for when the turbine is not operating in *SoLoNOx* mode. For such instances, the actual emission, ±20%, are estimated based on a combination of empirical calculations and the limited test data available. Table 3 provides esti-

Table 2. Expected Emissions below 0°F for Centaur 40 and Mars 90 Engines

Ambient	Fuel System	Fuel	NO _x , ppm	CO, ppm	UHC, ppm
Below 0°F	Gas only (50 to 100% load) <i>Centaur 40</i> and <i>Mars 90</i>	Gas	120	150	75
	Dual fuel (80 to 100% load) <i>Centaur 40</i> (Dual fuel not applicable for <i>Mars 90</i>)	Gas or Liquid	120	150	75

Table 3. Estimated Emissions

Engine Load	NO _x , ppm	CO, ppm	UHC, PPM
Less than 50%	70	2200	300
Idle	50	3500	500

**Solar Product Information Letter 168
VOC, SO₂, and HCHO Emission Estimates**

Concord Expansion Project
Compressor Station 270B1
Application for Temporary Permit

Volatile Organic Compound, Sulfur Dioxide, and Formaldehyde Emission Estimates

Leslie Witherspoon
Solar Turbines Incorporated

PURPOSE

The purpose of this PIL is to summarize methods available to estimate emissions of volatile organic compounds (VOC), sulfur dioxide (SO₂), and formaldehyde from gas turbines. Most customers are required to estimate emissions of these pollutants during the air permitting process.

INTRODUCTION

In absence of site specific or representative source test data, Solar refers customers to a United States Environmental Protection Agency (EPA) document titled "AP-42," or other appropriate EPA reference documents. AP-42 is a collection of emission factors for different emission sources. The emission factors found in AP-42 are a generally accepted way of estimating emissions when more representative data are not available. The most recent version of AP-42 (dated April 2000) can be found at <http://www.epa.gov/ttn/chief/ap42/index.html>.

Solar does not typically warranty the emission rates for VOC, SO₂, or formaldehyde.

Volatile Organic Compounds

Most permitting agencies require gas turbine users to estimate emissions of VOC, a subpart of the unburned hydrocarbon (UHC) emissions, during the air permitting process. Volatile organic compounds, non-methane hydrocarbons (NMHC), and reactive organic gases (ROG) are some of the many ways of referring to the non-methane (and non-ethane) portion of an "unburned hydrocarbon" emission estimate.

For natural gas fuel, most Solar customers use 10-20% of the UHC emission rate to represent VOC emissions. The estimate of 10-20% is based on a ratio of total non-methane hydrocarbons to total organic compounds. The use of

10-20% provides a conservative estimate and has been accepted by permitting authorities over the years. The 10% level assumption is most commonly used by customers in the air permitting process.

For liquid fuel, it is appropriate to estimate that 100% of the UHC emission estimate is VOC.

Sulfur Dioxide

Sulfur dioxide emissions are produced by conversion of sulfur in the fuel to SO₂. Since Solar does not control the amount of sulfur in the fuel, we are unable to generically predict SO₂ emissions. Customers generally estimate SO₂ emissions with a mass balance calculation by assuming that any sulfur in the fuel will convert to SO₂.

As an alternative to a mass balance calculation, EPA's AP-42 document can be used. AP-42 (Table 3.1-2a., April 2000) suggests emission factors of 0.0034 lb/MMBtu for gas fuel (HHV) and 0.033 lb/MMBtu for liquid fuel (HHV).

Formaldehyde

In gas turbines, formaldehyde emissions are a result of incomplete combustion. Formaldehyde in the exhaust stream is unstable and very difficult to measure. In addition to turbine characteristics including combustor design, size, maintenance history, and load profile, the formaldehyde emission level is also affected by:

- Ambient Temperature
- Humidity
- Atmospheric Pressure
- Fuel Quality
- Formaldehyde Concentration in the Ambient Air

- Test Method Measurement Variability
- Operational factors

Table 1 summarizes total hazardous air pollutants (HAP) and formaldehyde emission factors for gas turbines < 50MW in size. The emission factor data is taken from an EPA memo: "Revised HAP Emission Factors for Stationary Combustion Turbines, 8/22/03". The emission factors in the memo are a compilation of the HAP data EPA collected during the Maximum Achievable Control Technology (MACT) standard development process. The emission factor documentation shows there is a high degree of

variability in formaldehyde emissions from gas turbines, depending on the manufacturer, rating size of equipment, combustor design, and testing events. To estimate formaldehyde emissions from gas turbines, users should use the emission factor(s) that best represent the gas turbines actual/planned operating profile.

The 95% Upper Confidence of Mean and 95% Upper Confidence of Data emission factors from the August 22, 2003, memo are shown in Table 1. The EPA memo also presents HAP emission factors in the following categories: mean, median, maximum, and minimum.

Table 1. EPA's Total HAP and Formaldehyde Emission Factors for <50 MW Lean Premix Gas Turbines burning Natural Gas.

(Source: Revised HAP Emission Factors for Stationary Combustion Turbines, OAR-2002-0060, IV-B-09, 8/22/03)

Pollutant	Engine Load	95% Upper Confidence of Mean (lb/MMBtu HHV)	95% Upper Confidence of Data (lb/MMBtu HHV)	Memo Reference
Total HAP	> 90%	0.00144	0.00258	Table 19
Total HAP	All	0.00160	0.00305	Table 16
Formaldehyde	> 90%	0.00127	0.00241	Table 19
Formaldehyde	All	0.00143	0.00288	Table 16

Table 2 summarizes approximate ton per year formaldehyde emissions from Solar's current production models based on the 95% Upper

Confidence of Data emission factors as shown in Table 1 and ISO condition fuel flow data.

Table 2. Formaldehyde Emissions Estimates for Solar's Products (59°F, 60% RH, sea level, no losses)

Solar Turbine Model	Fuel Input, MMBtu/hr LHV (HHV)	Formaldehyde Emission Estimate, tpy	
		Using the 95% Upper Confidence of Data Emission Factor - All Loads	Using the 95% Upper Confidence of Data Emission Factor - > 90% Load
Saturn 20	16.8 (18.5)	0.23	0.20
Centaur 40	42.7 (47.0)	0.59	0.50
Centaur 50	50.3 (55.3)	0.70	0.58
Taurus 60	58.1 (63.9)	0.81	0.67
Taurus 70	71.9 (79.1)	1.00	0.83
Mars 90	99.2 (109.1)	1.38	1.15
Mars 100	111.5 (122.7)	1.55	1.29
Titan 130	132.0 (154.2)	1.83	1.53

In August, 2003, EPA finalized the combustion turbine Maximum Achievable Control Technology (MACT) standard. A gas turbine will be considered "new" if it is part of a project that commenced construction (enter into a contractual agreement) after January 14, 2003. "New" turbines at major sources of hazardous air pollutants (HAP), >10 tpy of a single HAP, >25 tpy of all HAPs, will need to comply with the MACT standard of 91 ppb.

As you can see from Table 2 it is unlikely that any multiple unit Solar turbine project will be a major source of HAPs. However, if a gas turbine is placed at a site that is a major source of HAPs due to other emission sources at the site

(most vulnerable customers include compressor stations with reciprocating engine base, chemical plants, and refineries), then the gas turbine MACT standard will be applicable.

If the MACT is applicable, new gas turbines will be required to meet 91 ppb formaldehyde. Source test data to date do not indicate that mid-range industrial gas turbines can meet the formaldehyde standard without the use of an oxidation catalyst. In fact, the preamble to the final MACT standard noted that the 91 ppb value is "post control", e.g. a measured level after a CO oxidation catalyst. With this in mind, Solar will not warranty formaldehyde at the 91 ppb level.

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Solar Product Information Letter 170
Startup and Shutdown Emissions

Emission Estimates at Start-up, Shutdown, and Commissioning for SoLoNOx Products

Leslie Witherspoon
Solar Turbines Incorporated

PURPOSE

Emissions during start-up, shutdown, and commissioning of Solar's size class of gas turbine are negligible and are not warranted by Solar. Without appropriate forewarning, however, many customers and regulators will treat Solar's turbines as though they were large utility turbines. The purpose of this PIL is to provide insight into the different situation with Solar's class of turbine and provide emission estimates for start-up, shutdown, and commissioning.

INTRODUCTION

Due to the surge of energy projects in the utility sector and the start-up and shutdown emission characteristics of large utility turbines, some regulatory agencies have been asking Solar's customers to account for emissions during start-up and shutdown conditions in their air permitting. The operating characteristics and emissions profile of Solar's size class of turbine is different than those of a utility-size combined-cycle power plant. This basic fact is often overlooked by regulatory agencies and can cause Solar's customers to expend significant effort in estimating start-up and shutdown emissions that are essentially insignificant. In most cases, once our estimated start-up emissions are relayed to the permitting engineers, the issue is dropped.

Start-up occurs in one of three modes: cold, warm, or hot. In general, the start-up duration for a hot, warm, or cold Solar turbine is less than 10 minutes in simple-cycle and most combined heat and power designs. Heat recovery steam generator (HRSG) steam pressure is usually 250 psig or less. At 250 psig or less, thermal stress within the HRSG is minimized and, therefore, firing ramp up is not limited.

A utility-size combined-cycle power plant typically operates at 1800 to 2400 psig. At 1800 to 2400 psig, a 2 to 3 hour start-up sequence is required for a **cold** start (steam turbine shutdown for greater than 72 hours), 1 to 2 hours for a **warm** start (steam turbine shutdown for 8 to 72 hours); and 30 minutes for a **hot** start (steam turbine shutdown for less than 8 hours). Large simple-cycle gas turbines generally start-up in 10 to 30 minutes.

Start-up, shutdown, and commissioning emissions will **not** be guaranteed by Solar Turbines. The information presented in this document is representative for both single and two-shaft engines only. Operation of duct burners and/or any add-on control equipment is not considered in the estimates.

START-UP EMISSION ESTIMATES

The start-up duration is the same for cold, warm, and hot starts. Expected start-up emissions are summarized in Table 1, in parts per million by volume (ppmv), and in Table 2, in pounds per year for each product. The emission estimates are calculated from empirical exhaust characteristics. Getting to the SoLoNOx mode takes three steps:

1. Purge-crank
2. Ignition and acceleration to idle
3. Loading / thermal stabilization

During the "purge-crank" step, rotation of the turbine shaft is accomplished with an electric starter motor to remove any residual fuel gas in the engine flow path and exhaust. During "ignition and acceleration to idle," fuel is introduced into the combustor and ignited in a diffusion flame mode

Table 1. Estimated Emissions during Start-Up (ppmv)

Start-up Step	Combustion Mode	Approx. Time, minutes	NOx, ppmv	CO, ppmv	UHC, ppmv
1. Purge-Crank	None	4	—	—	—
2. Ignition-Idle-Generator Synchronization	Diffusion	3	50	3500	500
3. Loading / Thermal Stabilization	Transitional	6	70	2200	300
4. 50% to Full Load	SoLoNOx	Variable	<25	<50	<25

and the engine rotor is accelerated to idle speed. The third step consists of applying up to 50% load while allowing the combustion flame to transition and stabilize. Once 50% load is achieved, the turbine transitions to SoLoNOx mode (Step 4) and the engine control system begins to hold the combustion primary zone temperature and limit pilot fuel to achieve the carbon monoxide (CO) and nitrogen oxides (NOx) emission levels.

The specific load at which a unit enters SoLoNOx mode (Step 4) varies by engine model and ambient temperature. For two-shaft engine, the SoLoNOx "trigger" load also varies by gas producer speed (NGP).

It is important to note that Steps 2 and 3 are short-term transient conditions making up less than 10 minutes. No emission guarantee is provided by Solar for <50% load. NOx, CO, and unburned hydrocarbons (UHC) are guaranteed at 25 ppmv, 50 ppmv, and 25 ppmv respectively, when operating greater than 50% load.

SHUTDOWN EMISSIONS

Normal, planned cooldown / shutdown duration varies by engine model. The *Centaur 40*, *Centaur*

50, and *Taurus 60* take about five minutes. The *Taurus 70*, *Mars 90* and 100, and *Titan 130* take about 10 minutes. Typically, the emissions will be similar to Start-up Step 4 for 90 seconds and Step 3 for the balance of the estimated duration (assumes unit was operating at full-load).

COMMISSIONING EMISSIONS

Commissioning generally takes place over a two-week period. Static testing, where no combustion occurs, usually requires one week and no emissions are expected. Dynamic testing, where combustion will occur, will see the engine start and shutdown a number of times and a variety of loads will be placed on the system. It is impossible to predict how long the turbine will run and in what combustion / emissions mode it will be running. The dynamic testing period is generally followed by one to two days of "tune-up" during which the turbine is running at various loads, most likely within low emissions mode (warranted emissions range).

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Table 2. Estimation of Start-up and Shutdown Emissions (lb/yr) for SoLoNOx Gas Fuel**Data will NOT be warranted under any circumstances**

	Centaur 40 4700S						Centaur 50 6200SII						Taurus 60 7600SII						Taurus 70 10300S					
	Exhaust Flowrate (lb/hr)	O ₂ %	H ₂ O %	NO _x (lbs)	CO (lbs)	UHC (lbs)	Exhaust Flowrate (lb/hr)	O ₂ %	H ₂ O %	NO _x (lbs)	CO (lbs)	UHC (lbs)	Exhaust Flowrate (lb/hr)	O ₂ %	H ₂ O %	NO _x (lbs)	CO (lbs)	UHC (lbs)	Exhaust Flowrate (lb/hr)	O ₂ %	H ₂ O %	NO _x (lbs)	CO (lbs)	UHC (lbs)
Start-up																								
Step 2 (3 min)	146,415	19.13	2.44	0.13	5.33	0.43	150,409	18.52	2.99	0.18	7.63	0.62	171,774	19.3	2.29	0.13	5.56	0.45	211,378	18.56	2.95	0.25	10.53	0.86
Step 3 (6 min)	146,415	19.13	2.44	0.35	6.70	0.52	150,409	18.52	2.99	0.50	9.59	0.75	171,744	19.3	2.29	0.37	6.99	0.54	211,378	18.56	2.95	0.69	13.24	1.03
Total Start-up Emissions				0.5	12.0	1.0				0.7	17.2	1.4				0.5	12.5	1.0				0.9	23.8	1.9
Shutdown																								
Step 4 (90 sec)	147,718	15.46	5.70	0.11	0.13	0.04	151,411	14.35	6.68	0.13	0.16	0.05	173,937	14.33	6.70	0.15	0.19	0.05	213,837	14.32	6.70	0.19	0.23	0.07
Step 3 (3.5 min)	146,415	19.13	2.44	0.20	3.91	0.30	150,409	18.52	2.99	0.29	5.60	0.44	171,744	19.3	2.29	0.21	4.08	0.32	211,378	18.56	2.95	0.98	18.76	1.46
Total Shut-down Emissions				0.3	4.0	0.3				0.4	5.8	0.5				0.4	4.3	0.4				1.2	19.8	1.5

	Mars 90 13000S						Mars 100 15000S						Titan 130 19500S					
	Exhaust Flowrate (lb/hr)	O ₂ %	H ₂ O %	NO _x (lbs)	CO (lbs)	UHC (lbs)	Exhaust Flowrate (lb/hr)	O ₂ %	H ₂ O %	NO _x (lbs)	CO (lbs)	UHC (lbs)	Exhaust Flowrate (lb/hr)	O ₂ %	H ₂ O %	NO _x (lbs)	CO (lbs)	UHC (lbs)
Start-up																		
Step 2 (3 min)	179,125	17.2	4.15	0.35	14.71	1.20	179,761	17.18	4.17	0.35	14.84	1.21	390,263	18.88	2.66	0.39	16.52	1.36
Step 3 (6 min)	179,125	17.2	4.15	0.97	18.49	1.44	179,761	17.18	4.17	0.98	18.65	1.45	390,263	18.88	2.66	1.09	20.76	1.62
Total Start-up Emissions (lbs)				1.3	33.2	2.6				1.3	33.5	2.7				1.5	37.3	3.0
Shutdown																		
Step 4 (90 sec)	318,755	15.0	6.11	0.25	0.31	0.09	331,545	14.62	6.44	0.29	0.36	0.10	394,751	14.39	6.64	0.35	0.42	0.12
Step 3 (0.5 min)	179,125	17.2	4.15	1.37	26.20	2.04	179,761	17.18	4.17	1.38	26.43	2.06	390,263	18.88	2.66	1.54	29.42	2.29
Total Shut-down Emissions (lbs)				1.6	26.5	2.1				1.7	26.8	2.2				1.9	29.8	2.4

Assumes ISO conditions 59F, 60% RH, sea level, no losses
 Exhaust flowrates for Step 2 and 3 from FASTE @ 1% load using diffusion flame equivalent model, Mars 90 and 100 use 10% load diffusion flame data
 Exhaust flowrates for Step 4 from FASTE @ 100% load using SoLoNOx models
 Assumes unit is operating at full load prior to shut-down.
 Assumes gas fuel

**Solar White Paper on:
Developments in Low Emissions Combustion Systems**

Developments in Low Emissions Combustion Systems for Industrial Gas Turbines

Solar Turbines

A Caterpillar Company

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Developments in Low Emissions Combustion Systems for Industrial Gas Turbines

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INTRODUCTION

In 1992, Solar introduced the first industrial gas turbines employing a lean-premixed combustion system for emissions control. Since then, Solar has placed more than 825 SoLoNOx™ gas turbines into service. These turbines routinely are meeting emissions limits as strict as 25 ppmv NOx and 50 ppmv CO (15% O₂) on natural gas. Other gas turbine manufacturers have followed suit and, at this time, nearly every manufacturer has introduced a low emissions gas turbine product line based on lean-premixed combustion technology.

Despite the significant improvements in gas turbine emissions over the last eight years, regulatory agencies continue to consider and implement more stringent emissions regulations. For example, NOx control levels for gas turbines have been set as low as 1 ppmv in Massachusetts. Levels this low require the use of expensive exhaust gas cleanup systems in addition to advanced low NOx combustion technology. CO levels as low as 10 ppmv may be required by future emissions regulations.

The primary purpose of this paper is to provide a broad overview of low emissions combustor development and how it is being shaped by emissions regulations that are continually changing. Discussed in this paper is a description of the development and present status of SoLoNOx; a discussion of how increasingly restrictive emissions regulations impact industrial gas turbine production; and a review of new combustion technologies with the potential to achieve lower emissions levels. Solar continues to explore combustion technologies in the belief that clean combustion is a more cost-effective path to low emissions than exhaust gas cleanup.

LEAN-PREMIEXED COMBUSTION

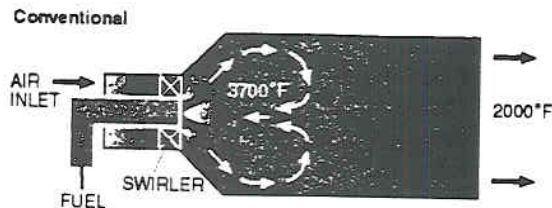
SoLoNOx employs lean-premixed combustion to reduce NOx emissions. Lean-premixed combustion reduces the conversion of atmospheric nitrogen to NOx by reducing the combustor flame temperature. Since NOx formation rates are strongly dependent on flame temperature, lowering flame temperature (by lean operation) is an extremely effective strategy for reducing NOx emissions (Figure 1). Lean combustion is enhanced by premixing the fuel and combustor airflow upstream of the combustor primary zone. This premixing prevents stoichiometric burning locally within the flame, thus ensuring the entire flame is at a fuel lean condition.

There are three aspects of lean-premixed combustion that warrant attention:

- CO/NOx tradeoff
- Combustor operating range
- Combustor pressure oscillations

CO/NOx Tradeoff

Since the flame temperature of a lean-premixed combustor is designed to be near the lean flammability limit, lean-premixed combustor performance is characterized by a CO/NOx tradeoff (Figure 2). At the combustor design point, both CO and NOx are below target levels; however, deviations from the design point flame temperature cause emissions to increase. A reduction in temperature tends to increase CO emissions due to incomplete combustion; an increase in temperature will increase NOx. This tradeoff must be addressed during part-load turbine operation when the combustor is required to run at an even leaner condition. The tradeoff also comes



Notes:

- (1) Conventional Combustors Have High Flame Temperatures
- (2) SoLoNOx Combustors Operate with Lower Flame Temperatures and Lower NOx Emissions
- (3) NOx Emissions Increase Rapidly with Flame Temperature

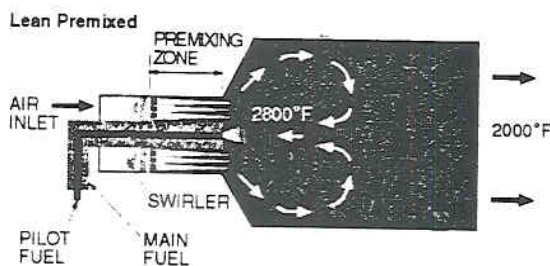


Figure 1. How Lean-Premixed Combustion Reduces NOx Emissions

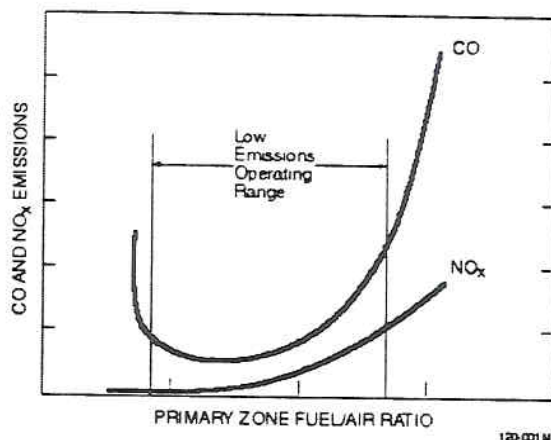


Figure 2. Typical Lean-Premixed Combustor Emissions

into play in development efforts to reduce lean-premixed combustor NOx emissions by further reducing the primary zone design point temperature.

Combustor Operating Range

In a gas turbine, the lean-premixed CO/NOx tradeoff is manifested as a limited load range

over which emissions limits can be satisfied. As a gas turbine moves away from full-load operation, a lean-premixed combustor will eventually produce excessive CO emissions.

To broaden the operating range, low emissions gas turbines can use variable geometry to maintain the combustor primary zone at its optimum low emissions point despite load changes. Variable geometry involves combustor airflow control within the gas turbine to maintain a nearly constant flame temperature.

The current generation of low emissions gas turbines uses either compressor air bleed or variable geometry at part-load to broaden the operating range of the lean-premixed combustion system. Although effective, compressor bleed results in a reduction in part-load efficiency because high-pressure air is vented to the atmosphere upstream of the gas generator.

Some applications such as single-shaft gas turbines can use the inlet guide vanes (IGV) to perform the variable geometry function without an efficiency impact; however, the IGV technique is not applicable to two-shaft gas turbines.

Combustor Pressure Oscillations

The introduction of lean-premixed combustion systems for gas turbines has raised manufacturer awareness of the consequences of large combustor pressure oscillations. Simply put, lean flames have a greater tendency to cause pressure oscillations that can lead to engine damage. It is recognized that the reduced stability of a lean-premixed flame contributes to combustor oscillations. Despite increased awareness, however, manufacturers are still working to develop design methodologies and combustion system features that prevent excessive combustor pressure oscillations.

The three lean-premixed combustion system characteristics previously identified represent significant constraints in efforts to develop advanced combustion systems that will further reduce gas turbine NOx and CO emissions.

SOLONOX DEVELOPMENT

In 1987, Solar began a major development effort to integrate dry, low NOx combustion technology into its product line. Several potential low NOx combustion techniques were

evaluated and lean-premixed combustion was selected as the most promising approach for near-term application. Advantages of lean-premixed combustion include the concept's proven potential for low NO_x emissions, general similarity of combustion system hardware to that used in conventional gas turbines, and Solar's extensive lean-premixed technology base developed through earlier research work.

Combustion System Description

Development of the SoLoNO_x combustion system required modifications to the following engine components:

- Combustor Liner
- Fuel Injectors
- Variable Geometry Systems
- Engine Casings
- Control System
- Fuel System

Combustor Liner

The lean-premixed combustor liner is generally similar to a conventional liner in terms of geometry, materials and construction (Figure 3). The most significant difference in the lean-premixed liner is an increase in combustor volume. The larger volume is required to ensure complete combustion and low CO and UHC emissions at the lower overall flame temperature of the lean-premixed combustor (Figure 4). Since combustor length was constrained by the engine exchangeability objective, the increased combustor volume was achieved by increasing the outer liner diameter. The larger liner required an increase in the diameter of the combustor housing (Figure 5).

A second difference in the lean-premixed liner is the absence of large air injection ports in the combustor primary zone. All air used in the combustion process is introduced through the air swirlers of the fuel injectors. Remaining compressor delivery air is used for cooling the walls or for dilution to achieve the specified radial temperature profile and pattern factor at the combustor exit.

Early SoLoNO_x combustor liners incorporate conventional air film louver wall cooling techniques. More recently, an improved effusion-cooled liner design has been developed

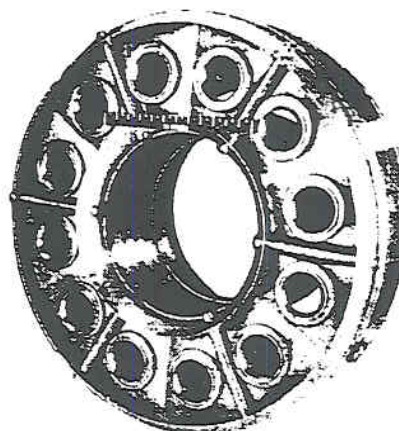


Figure 3. Lean-Premixed Annular Combustor Inlet Section

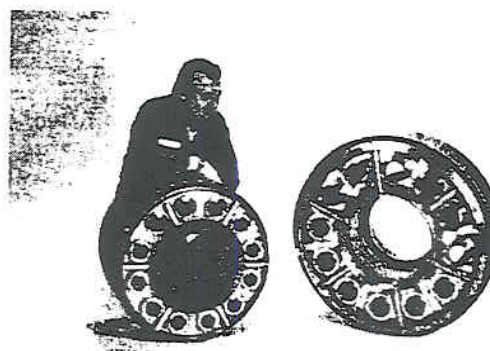


Figure 4. Comparison of Conventional and SoLoNO_x Combustor Liners

to give improved CO compliance at ambient temperatures below -20°C (0°F).

The first production SoLoNO_x combustors used louvers on the inside of the liner to direct air axially along the walls to produce a protective film of cooling air between the wall and the hot combustion gases (Figure 6). This method of liner cooling is commonly used in industrial and aircraft gas turbine combustors. The cooling air film gradually mixes with the hot gas stream; thus, a succession of louvers must be placed along the liner to maintain the required temperatures. This method of wall cooling uses relatively high levels of cooling air, because the wall just downstream of the louver must be overcooled in order to keep the wall adjacent to the next louver below the maximum temperature limit.

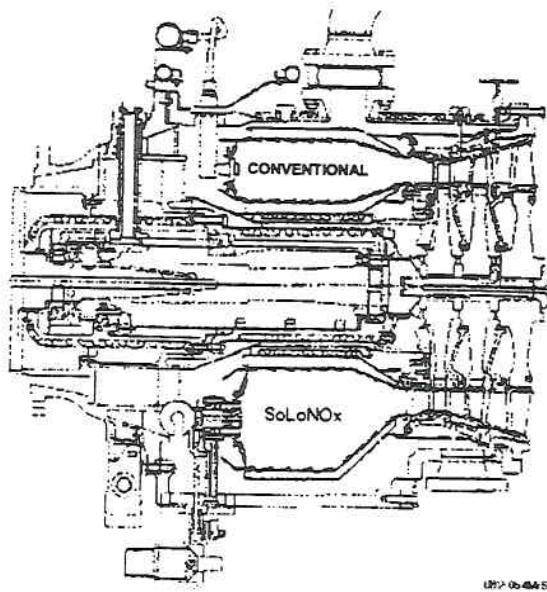


Figure 5. Comparison of Conventional and SoLoNOx Combustion Systems

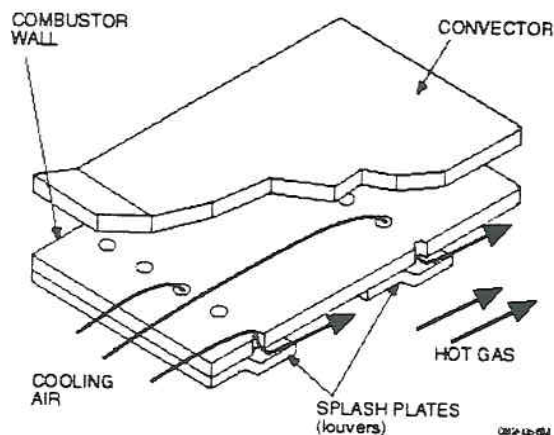


Figure 6. Louver Cooling Design

Effusion cooling of the combustor walls has been developed for SoLoNOx combustor liners in order to reduce the cooling air required and, in turn, reduce CO emissions.

The injection of cooling air along the combustor wall can quench the combustion reactions in the wall region, thus contributing to CO and UHC emissions.

The basic geometry of the effusion-cooled liner is the same as the louvered version. Effusion cooling is obtained by starting a film of air with a cooling louver at the front of the combustor and then continuously feeding this film

with additional air through a multitude of small diameter holes laser drilled at an angle of 20 degrees to the wall surface (Figure 7).

An effusion liner has the total cooling air reduced by about 20% relative to the louvered liner. Thermal gradients in an effusion liner are significantly less than in the louvered liner while still maintaining acceptable wall temperatures. Additional cooling effectiveness is achieved by adding an impingement shield to the SoLoNOx combustor liner and combining air impingement on the back side of the combustor wall with effusion through the wall (Figure 8).

As Solar continues to develop lower emissions combustion products, combustors using only back-side convective cooling are being introduced. The total avoidance of cooling air

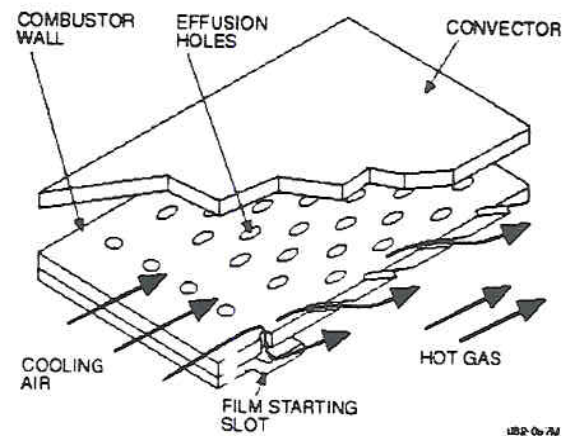


Figure 7. Effusion-Cooling Design

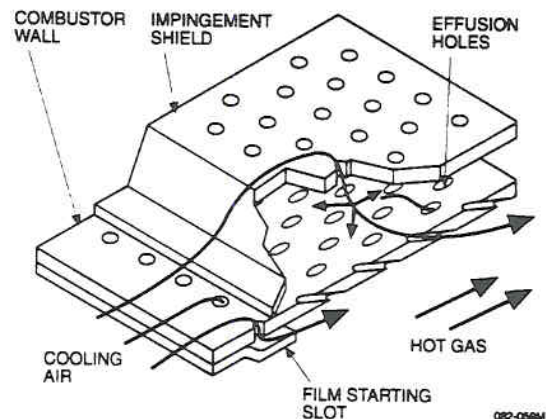


Figure 8. Impingement/Effusion-Cooling Design

injection into the combustor primary zone allows greater latitude for combustor optimization for minimum NO_x and CO.

Fuel Injectors

SoLoNO_x fuel injectors (Figure 9) are significantly larger than their conventional counterparts due to the higher airflow through the injector air swirlers and the required volume of the premixing chamber used to mix the fuel and air. The injector module includes a premixing main fuel injector, a pilot fuel injector, and in some cases a variable geometry system for part-load control purposes.

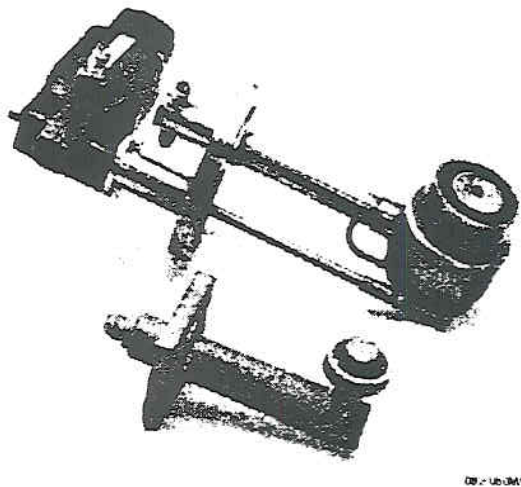


Figure 9. Comparison of SoLoNO_x and Conventional Fuel Injectors

Main Fuel Circuit. The premixing main fuel injector uses an axial swirler to impart a high degree of swirl to the primary zone air. A series of multi-orificed, radial-fuel tubes injects natural gas fuel into air just downstream of the air swirler. Uniform mixing of the fuel and air occurs within the annular premixing chamber prior to reaching the combustor primary zone. The strong swirl stabilizes the combustion process in the primary zone by establishing a recirculation zone that draws reacted hot gases back upstream, thus providing a continuous ignition source. Above 50% engine load, the majority of the fuel (approximately 90 to 100%) is introduced through the main fuel tubes.

Pilot Fuel Circuit. The pilot fuel injector circuit is used mainly for lightoff and low-load operation. The pilot fuel injector consists of an air swirler and tangential fuel inlet ports to provide partial premixing of air and fuel prior to combustion. During lightoff and low-load operation, approximately 30 to 50% of the fuel passes through the pilot injector, providing a rich fuel/air mixture. Combustor stability is enhanced in this mode compared to lean-premixed operation, although NO_x and CO emissions are higher. Above 50% engine load, the pilot fuel is reduced to less than 10% of the total fuel flow to optimize emissions performance. The pilot fuel is also momentarily increased during off-load transients to help stabilize the flame during the transient.

Variable Geometry Systems

Several variable geometry systems have been employed to avoid lean extinction and broaden the low emissions operating range of the lean-premixed SoLoNO_x combustion system. Each technique provides control of the primary zone airflow to maintain the primary zone fuel/air ratio near its optimum low emissions level during part-load engine operation.

Casing Bleed. Two-shaft gas turbines used for gas compression and mechanical drives, bleed air from the combustor casing at part load. This method of variable geometry has proved effective in controlling the CO emissions while using the production bleed valve of conventional engines. A consequence of air bleed, however, is a deterioration in engine part-load thermal efficiency, since the compressed bleed air no longer enters the turbine section of the engine to produce power.

Inlet Guide Vanes. Single-shaft gas turbines used for power generation, maintain optimum primary zone fuel/air ratios by modulating the compressor IGVs. Closing the IGVs reduces the airflow through the engine compressor and combustor. No bleeding of high-pressure air is required.

Swirler Inlet Valve. In addition to casing bleed, *Centaur* 40S, *Centaur* 50S, and *Taurus* 60S gas turbine fuel injectors have a two-position swirler inlet valve (SIV) located up-

stream of the main air swirler, which is used to control the airflow into the combustor primary zone. This valve is pneumatically actuated from outside the combustor casing. In the open position, full airflow passes through the swirler. In the closed position, the slotted SIV reduces the primary zone airflow. By closing the SIV, the primary zone fuel/air ratio is changed in a step-wise fashion. Additional low emissions combustor operating range is obtained without any heat rate penalty.

Engine Casings

Larger combustor casings are required for the SoLoNOx system due to the increased diameter of the combustor liner and larger fuel injectors. This larger combustor case also requires modification to the mating compressor diffuser and gas producer turbine cases. The overall length of the engine remains unchanged.

Control System

The SoLoNOx gas turbine control system is identical to the conventional gas turbine system at start-up and low-load operation, but differs when the gas turbine operates in the low emissions mode (above approximately 30 to 50% of the rated load). The control system for SoLoNOx engines modulates the variable geometry systems to keep the combustion primary zone temperature within a specified range. Accurate control of the primary zone temperature is critical to controlling NOx and CO emissions. Direct measurement of this temperature, which is greater than 1540°C (2800°F), over an extended period of time is impractical, however. Conventional gas turbines use the power turbine inlet temperature (T5) as an indirect measurement of the combustor exit or turbine inlet temperature. The SoLoNOx gas turbines also use this same T5 for control.

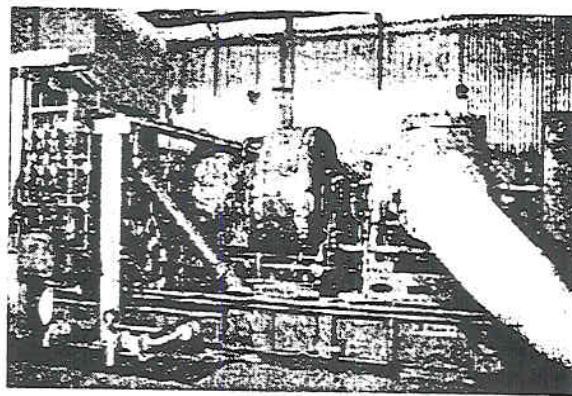
Fuel System

The natural gas fuel system for SoLoNOx gas turbines includes two separate fuel circuits: one for the pilot system and one for the main. Separate fuel manifolds are used to supply pilot and main gas to the respective fuel circuits of each fuel injector. The fuel flow split between main and pilot is controlled with a

precision electronic valve on the pilot line. During start-up and low-load operation, high-flow rates of pilot are used. When the engine is in the low-emissions mode, the pilot fuel valve throttles the pilot valve to low levels. The low-pilot flow is used to stabilize the flame.

Initial Field Test Engines

The first prototype production SoLoNOx gas turbines used in gas transmission service were installed at customer field evaluation sites in 1992. A *Centaur* 50S gas turbine, rated at 4100 kW (5500 hp), was installed at the El Paso Natural Gas Company (EPNG) Window Rock Station near Window Rock, Arizona (Figure 10). In mid-1992, a *Mars* 100S gas turbine, rated at 10 500 kW (14,000 hp), was installed at the Pacific Gas Transmission (PGT) station near Rosalia, Washington.



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Figure 10. Centaur 50S Engine Installed at EPNG, Window Rock Station, Arizona

Production Engines

Production *Centaur*, *Taurus*, *Mars* and *Titan* SoLoNOx gas turbines are now in service as prime movers for gas transmission, mechanical-drive applications, and power generation throughout the U.S., Canada, Europe, and Japan. These engines have demonstrated the capability of meeting the emissions guarantees at ambient temperatures between -20°C (0°F) in Canada and 50°C (120°F) in the Arizona/California desert. Operation has also been successful on lower Btu fuels such as the

Dutch Groningen gas, but with slightly higher CO emissions than natural gas. The experience to date has shown excellent durability of the SoLoNOx combustion hardware. Inspections of the high time engines indicate that these engines will have life expectancies equivalent to Solar's conventional engines. Table 1 presents a compilation of SoLoNOx engine operating experience.

Table 1. SoLoNOx Experience through June 2001

Type	Units Sold	Estimated Hours
Centaur 40	88	2,910,000
Centaur 50	102	1,130,000
Taurus 60	335	6,080,000
Taurus 70	127	1,180,000
Mars 90/100	180	2,475,000
Titan 130	38	63,000
Total	870	13,838,000

Dual Fuel Capability

The need to provide low emissions dual fuel capability for power generation applications presents its own set of complexities and technical challenges. The injector designs (Figure 11) become physically complex and the operability issues relative to long-term injector durability and maintenance are challenging.

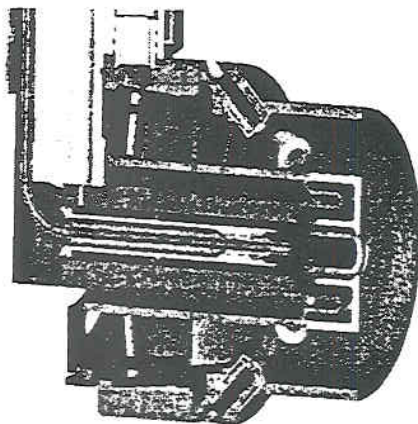


Figure 11. Typical Dual Fuel Injector Design

Solar has been building field experience with dual fuel SoLoNOx capability since 1995. There are now more than 100 dual fuel, low-emissions engines successfully operating in the field.

The major technical challenge is injector coking, in steady-state operation as well as during fuel transfers. Over the last two years, significant improvements have been made in the capability of the associated purge systems and a number of enhancements required in fuel handling have been defined. The current injector design and development efforts are focused on long-term coking issues with the high temperature and pressure environment in which the injector operates, while continuing to focus on lower emissions capability on liquid fuel.

MAINTAINING PRODUCT STABILITY

It is understandable that one might assume that SoLoNOx is a mature Solar gas turbine technology, since nine years have passed and hundreds of turbines have been installed since 1992. Yet, numerous forces have been at work over this period that have required SoLoNOx to evolve technically. A look to the future suggests that these same forces will continue to act. To continue to meet market requirements, SoLoNOx, as well as other dry low emissions (DLE) systems, will have to evolve. The forces that are driving the evolution of SoLoNOx include:

- Continuing need to reduce NOx emissions to meet increasingly strict air quality regulations.
- Promulgation of increasingly strict CO emissions limits.
- Market desire for dual fuel capability (natural gas and No. 2 distillate) at many power generation sites and the growing desire to use a broad range of alternate fuels that need to have no visible smoke when operating on liquid fuels, even during transient operation.
- Product cost reductions.
- Need to uprate engine performance over time to meet customer requirements.
- Desire to introduce new turbine products to provide a more diversified product line.

- Ability to address technical “surprises” that arise during product introduction or extended operation in the field. A prime example is the occurrence of unacceptably high combustor pressure oscillations, which have forced combustion system design changes throughout the entire gas turbine manufacturing community.

In this environment of ever-changing driving forces, it is unlikely that low-emissions combustion systems will be able to maintain complete design stability.

Combustor Performance Functions

A well-designed gas turbine combustor must satisfy a wide range of performance criteria. The primary goal of achieving essentially 100% combustion efficiency is only one of many requirements. Other requirements include:

- Producing a specific radial exit temperature profile in the gas flow delivered to the turbine section of the engine.
- Having a generally uniform circumferential exit temperature (as reflected in the pattern factor) to ensure turbine nozzle durability.
- Having sufficient operating stability to permit engine light-off and acceleration to full-load conditions.
- Providing combustion stability during large on-load and off-load transients operating without excessive combustor pressure oscillations.
- Maintaining sufficiently low material temperatures to meet durability requirements (30,000 hours for Solar) even under highly cyclic operating conditions.
- Burning widely different fuels (gases and liquids) in gas only and dual fuel systems.
- Avoiding coking of combustor components during liquid fuel operation.
- Functioning acceptably with engine inlet temperatures that may range from 0°F to over 120°F.
- Functioning acceptably in different configurations of the same turbine product. For example, gas turbines for power generation have different operating characteristics than engines for mechanical

drive applications. In addition, operating characteristics may vary in engines that are specifically designated to operate at extremely hot or extremely cold customer sites.

- Meeting all of the above requirements while maintaining trace emissions concentrations (NO_x, CO and UHC) at low, parts per million levels.

Clearly, combustor development can be a challenging activity, particularly when stringent emissions requirements exist. Compounding this challenge is the complexity of the gas turbine combustion process. The combustion process involves highly turbulent, reacting, high temperature, two-phase (for liquid fuels) flows that defy accurate quantitative modeling. Consequently, commercial combustor development always involves an iterative process of analysis, design, and performance testing.

Meeting Emissions Guarantees

Although gas turbine output, efficiency and cost are the most important considerations for the majority of turbine operators, emissions have become a “gate” through which turbines must pass to compete in emissions-sensitive markets.

Simplistically, the turbine manufacturer has two emissions-related milestones that must be met to ensure a viable low emissions product. First, the turbine manufacturing process must be sufficiently repeatable to ensure that new engines consistently meet their emissions guarantees during both pre-shipment testing and engine start-up at the customer’s site. In addition, the manufacturer must establish a design that is sufficiently robust to meet emissions guarantees over an extended period of operation at the customer’s site.

Meeting Emissions Guarantees at the Factory

By and large, the major challenge in routinely meeting emissions guarantees with new engines relates to airflow management within the turbine. Production processes and tooling must be maintained so that the precise airflow distribution required within the engine is achieved. This includes the percentage of air flowing to the fuel injectors, the liner and through other

passages used to cool turbine components downstream of the combustor. Manufacturing variations in any of the injector flow areas (there are 12 to 14 nominally identical injectors in Solar's low emissions engines), in the open area of the combustor liner, or in the orifices used to control turbine cooling will have a direct impact on the flame temperature in the primary zone of the combustor. Since NO_x emissions are exponentially sensitive to flame temperature, airflow distribution is critical in meeting emissions guarantees. If too much air passes through the one or more of injectors, CO emissions may be excessive. If too little air enters the combustor through the injectors, NO_x emissions may be higher than guaranteed.

Other factors that influence the emissions achieved with new turbines include:

- Uniformity with which fuel is delivered to each of the 12 to 14 injectors. Non-uniform fuel flows will lead to non-uniform flame temperatures in the combustor. High local flame temperatures will contribute to high NO_x while low temperature zones may cause excessive CO emissions.
- Variable rates of air leakage through seals between the combustor and other engine components can lead to air maldistributions. Seals must provide for differential thermal expansion between engine components without allowing excessive air leakage through the seal.

One final phenomenon that impacts engine test success relates to the occurrence of unacceptably high combustor pressure oscillations. Combustor oscillations tend to be of the "rumble" type (below 100 Hz) or of the "buzz" type (200 to 500 Hz). Excessive oscillations can lead to higher levels of emissions and, ultimately, liner component failure due to high-cycle fatigue. At the present time, the elements of combustor design that lead to high amplitude oscillations are receiving significant attention in the industry and are becoming better understood.

The primary means of combating oscillations is through the use of pilot flames to enhance the stability of the main flames downstream of each fuel injector. In cases where

oscillations occur, the amount of fuel needed for the pilot injectors varies from engine to engine. This is largely a reflection of manufacturing variability. In extreme cases, the pilot fuel required to dampen oscillations may be so large as to push NO_x emissions above guaranteed levels. Combustor pressure oscillations are undoubtedly the most frustrating characteristic of lean-premixed combustion systems. Two engines, nominally identical, may have very different levels of oscillations. Attempts to correlate oscillations with engine hardware characteristics (manufacturing variances) have not been completely successful.

Meeting Emissions Guarantees in the Field

The sensitivity of emissions to combustor and engine component design features was discussed above. From that discussion, it is clear that degradation in the combustion system components through extended operation in the field may also impact emissions. The potential mechanisms for emissions degradation are many, including:

- Poor fuel quality that contaminates fuel valves and injector passages, compromising performance of these components.
- Poor air quality and/or maintenance practices that lead to excessive compressor blade fouling.
- Mechanical failures of bleed valve actuators and fuel system valving.
- Fretting of component interfaces that leads to increased air leakage with time.
- Blockage of liquid fuel ports or the degradation of liquid fuel injection patterns due to coking.
- Fuel leakage within the injectors due to thermal or mechanical stresses. The need for dual fuel injectors to have gas and liquid fuel main passages, gas and liquid fuel pilot passages, and a pilot air passage makes these injectors very complex.

Since component life is affected by turbine duty cycle, so too are emissions. Engines experiencing frequent cyclic loading and engines operated at peak conditions can be expected to show degradation in hardware

more rapidly and have a higher potential for undesirably high emissions.

Additionally, regarding turbine component degradation with time, two other factors may be significant in causing turbine emissions to be different in the field from emissions measured at the factory. First, a wider variation in ambient temperatures at the operator's site will almost always occur relative to Solar's test venue in San Diego. Extremely hot or cold ambient conditions will impact NOx and CO emissions. In addition, since natural gas and No. 2 diesel are not pure fuels, fuel composition variations can cause variations in emissions levels. This may not only occur between two different test sites, but also at an operator's site where significant fuel composition variations occur over the life of the engine.

Product Stability Status

Based on the rapidly growing experience base with lean-premixed combustion systems, gas turbine manufacturers are now well aware that emissions are extremely sensitive to a number of factors, some of which are beyond the control of the manufacturer. These factors include:

- Combustor and engine design parameters
- Manufacturing variability
- Ambient conditions
- Fuel composition variations
- Component degradation over time
- Fuel quality (contaminants)
- Engine duty cycle
- Combustor pressure oscillations

The development of robust low emissions gas turbines across a product line is now fully appreciated as the formidable task that it is. Low emissions turbine development in a regulatory environment in which the emissions targets are changing with time and are established on a regional basis adds additional complexity to an already complex task. Manufacturers have to stretch their development resources to address issues at two levels. At the first level, the challenge is to maintain a growing fleet of engines and assure that current emissions regulations can be met. At another level, resources are needed to continue technology development for the stricter

emissions requirements that are anticipated for the future, but not quantified definitively (either control level or implementation date). Virtually every aspect of gas turbine manufacturing is in a cascade effect (Figure 12). The engineering and manufacturing challenges are considerable. The costs to the manufacturer are much greater than the cost increments reflected on the engine price tag.

In light of the now recognized technical challenges, the progress made in the last nine years in reducing gas turbine NOx emissions from hundreds of parts per million to under 25 ppm should be recognized as a major technical achievement and a significant factor in improved air quality. However, the regulatory trend towards ever-lower emissions levels is driving the development of further advancements in combustion system technologies.

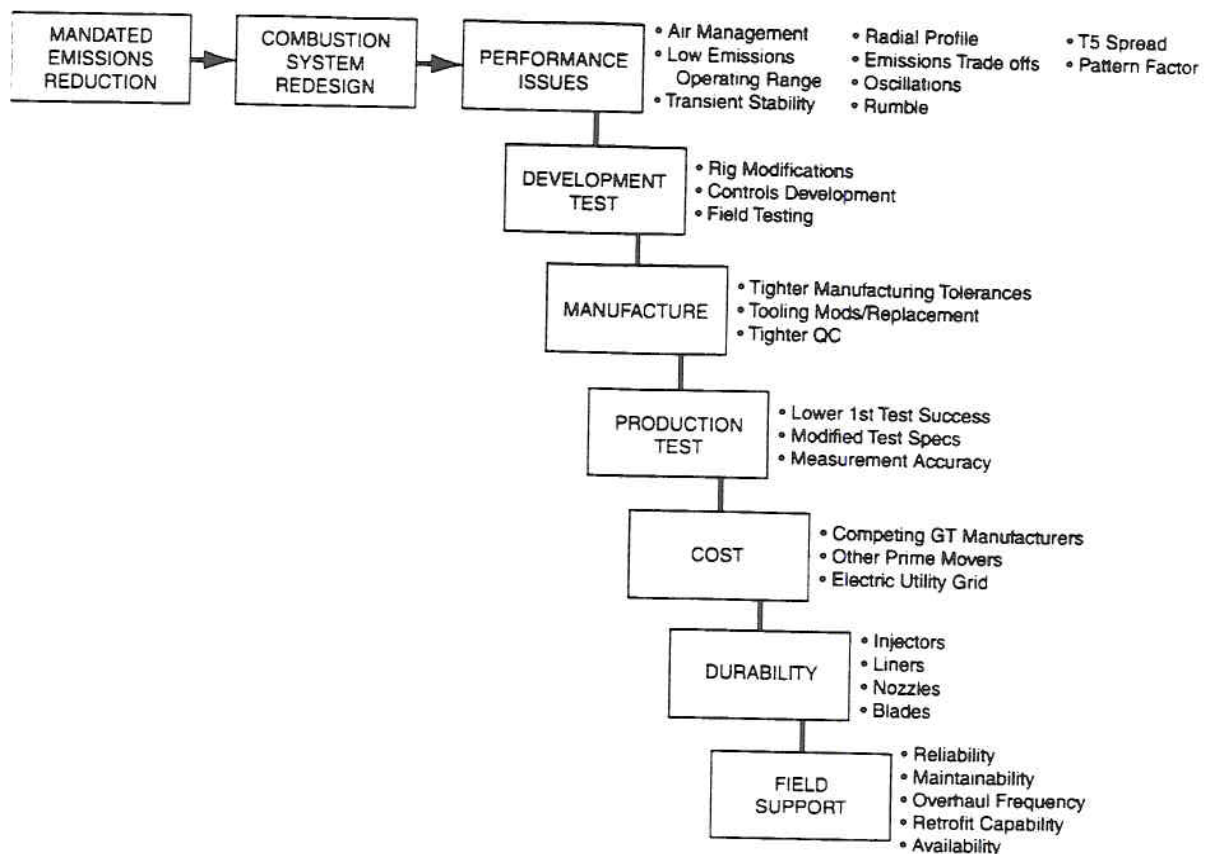
ADVANCED COMBUSTION TECHNOLOGIES

In response to the trend toward more stringent emissions regulations, gas turbine manufacturers are assessing their current lean-premixed systems to establish viable combustion system technology enhancements. The areas that exhibit the greatest potential for lower emissions include advanced combustor liners, more effective variable geometry systems, integration of control systems, and alternative combustion processes.

Advanced Combustor Liners

The present generation of lean-premixed combustors primarily uses film cooling to maintain acceptably low combustor wall temperatures. Film cooling involves the passage of cooling air through holes in the liner and the formation of a cooling film on the hot side of the liner using internally positioned louvers.

Research has shown that the method used to cool a lean-premixed combustor liner can have a significant effect on emissions. Specifically, conventional film cooling can lead to reaction quenching at the combustor primary zone wall. This quenching process leads to high CO emissions because the CO, a combustion intermediate, is prevented from oxidizing to CO₂. The quenching is traceable to the injection of a relatively large flow of cooling air into the primary zone.



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Figure 12. Cascading Effects of Reduced Emissions Limits

The development of an advanced liner with a "hot wall" that does not promote reaction quenching will provide a two-fold benefit in terms of emissions. First, of course, CO emissions will be reduced. Additionally, the lower CO levels will allow combustor reoptimization to a lower flame temperature. This will produce lower NO_x levels along with the lower CO concentrations, as illustrated in Figure 13.

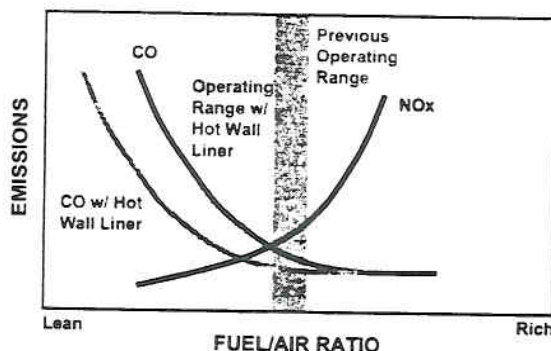


Figure 13. ABC Combustor Cross Section

Development work is or going in an effort to mitigate the reaction-quenching characteristic of film cooling. Technologies being studied include both augmented backside cooled (ABC) and ceramic combustor liners.

Augmented Backside Cooled Liners

ABC liners forego cooling air injection completely. Instead, combustor wall temperatures are controlled solely through convective cooling by a high velocity airstream on the cold side of the liner (Figure 14). In most instances, the high heat flux from the flame requires augmenting of the backside convective process to keep liner wall temperatures from becoming excessive. Turbulators in the form of trip strips, fins, and pins act to increase the cooling flow turbulence at the liner wall and augment the heat removal process. An alternative approach is to use impingement cooling with cooling flows through the outer convector.

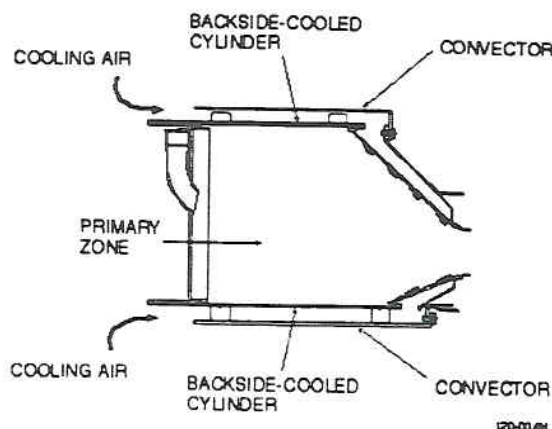


Figure 14. ABC Combustor Cross Section

Although effective in reducing CO formation through quenching, backside cooling is a challenge to implement because of the high flame temperatures and heat fluxes associated with gas turbine combustors. An additional degree of liner protection can be achieved through the application of a thermal barrier coating (TBC) on the hot sides of the liner walls. These TBCs are frequently composed of zirconia-based materials that are plasma-sprayed on the liner. A typical TBC coating of approximately 0.25 mm (0.01 in.) can reduce wall temperatures by approximately 40C° (72F°).

Ceramic Combustor Liners

The ceramic combustor addresses the CO quenching issue in the same manner as the ABC liner. Cooling air injection through the liner is avoided, thus providing potential emissions benefits. These emissions benefits have been found to be very similar to those of the ABC combustor.

In the ceramic combustor configuration employing a continuous fiber ceramic composites (CFCC) design, the inner and outer combustor cylinders, which form the combustor primary zone, have been redesigned to incorporate CFCC cylinders. The ceramic cylinders are housed within metallic cylinders that bear the structural and pressure loads on the assembly.

The advantage of the ceramic combustor versus an ABC combustor is that ceramic materials can tolerate higher temperatures. Typical CFCC materials are expected to give

good service at liner temperatures near 1100°C (2011°F) as opposed to the 850°C (1560°F) limit for typical metallic combustor liners. Monolithic ceramics can tolerate even higher temperatures, but are characteristically brittle. Currently, the high risk of turbine damage from these brittle materials effectively precludes their use in an industrial gas turbine.

Although CFCCs can tolerate higher temperatures, when used as a combustor material they still require cooling. Back-side cooling of the primary zone CFCC cylinders is needed to moderate wall temperatures for good durability. Use of a metallic housing for the CFCC liners makes it more difficult to achieve adequate CFCC cooling.

Development Status

Initial development work on both the ABC combustor and ceramic combustor has been directed at the *Centaur* 50 gas turbine in a joint Solar/U.S. Department of Energy (DOE) program. One of the primary program goals is to explore the potential for lower emissions using these advanced combustor technologies.

The ABC combustor utilizes a backside-cooled primary zone with the dome and dilution sections maintaining the current production metal configuration (Figure 15). A yttria-stabilized zirconia TBC is applied to the hot sides of the two primary zone cylinders.

Testing to date has been very successful. A short in-house gas turbine test documented performance and acceptable wall temperatures was completed to evaluate the TBC spalling

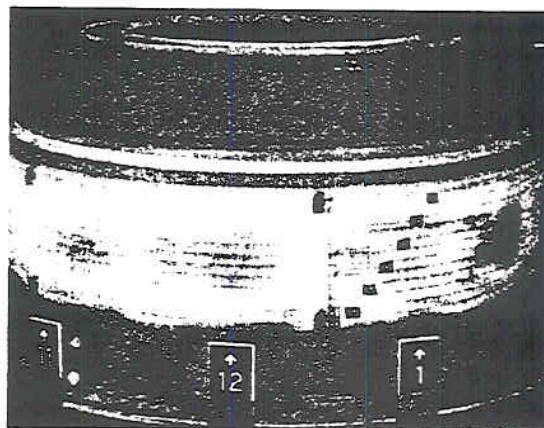


Figure 15. ABC Combustor for Centaur 50S Gas Turbine

at full-load conditions. A 50-hour cyclic test resistance. Results from both tests were encouraging and significant emissions reductions with this liner design observed. Figure 16 presents typical ABC liner emissions data.

At the present time, a field test of a production prototype *Centaur 50* ABC combustor is ongoing. The field test will demonstrate performance over an extended time period and over a wider range of turbine operation. More than 22,000 hours of successful operation have been logged.

The prototype ceramic combustor design parallels the ABC design (Figure 17). The primary zone combustor cylinders of the production *Centaur 50* gas turbine liner were replaced with SiC CFCC cylinders manufactured by DuPont Lanxide and B.F. Goodrich. The combustor has undergone extensive testing at Solar in both combustor rigs and an in-

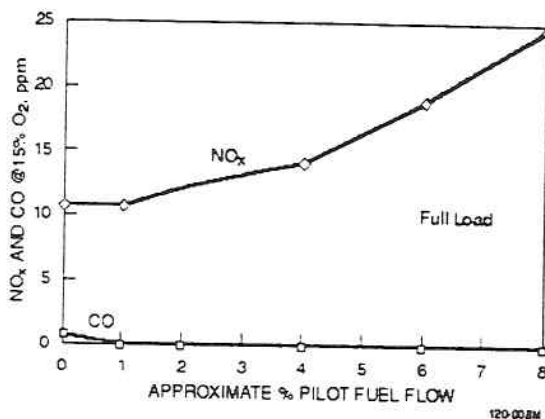


Figure 16. Typical ABC Liner Emissions (Full Load)

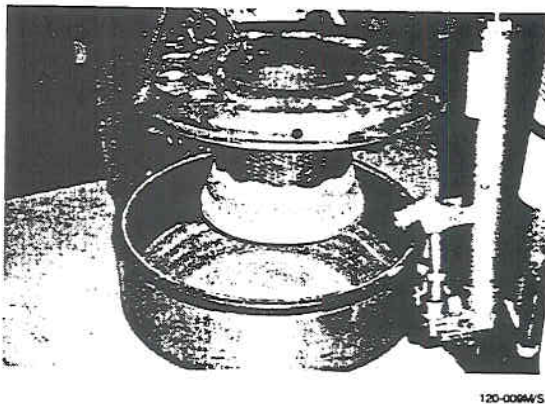


Figure 17. CFCC Liner for *Centaur 50S* Gas Turbine

house gas turbine. The testing has documented that the CFCC combustor meets all performance goals established for the liner and has emissions essentially identical to the ABC combustor.

At this point, the development focus is on CFCC material durability. In a 4000-hour field evaluation, the CFCC cylinders showed a moderate degree of oxidation. It has been determined that the 1200°C (2190°F) temperature limit specified early in the program for these materials is too high for a gas turbine environment. Design modifications have been completed to augment the cooling of the CFCC cylinders and drop the temperatures to the 1100°C (2011°F) level. Durability is expected to increase at the lower temperature. Field testing of this combustor design is underway.

In general, Solar's development results have demonstrated a significant emissions advantage with the ABC combustor. This technology is now being implemented in *SoLoNOx* engines with the *Centaur 50* and *Taurus 60* gas turbines being the first engines to use the ABC liner.

Variable Geometry Systems

Variable geometry systems provide control over the airflow entering the gas turbine combustor primary and dilution zones. In a non-variable geometry combustion system, the flow split between the primary and dilution zones remains constant as turbine load varies. As a result, the operating range over which low emissions can be maintained is quite narrow. Varying the combustor airflow split allows the primary zone stoichiometry to be maintained at an optimum condition across a larger portion of the turbine load range. The ultimate benefit is a wider range of low emissions operation due to a finer degree of control over the combustion process.

Current lean-premixed gas turbines use compressor air bleed or IGV modulation to perform the variable geometry function. Although effective, both approaches have a negative impact. Air bleed results in a loss in turbine efficiency at part load. IGV modulation is suitable only for single-shaft gas turbines, where the compressor and gas generator are mechanically linked. In cogeneration applications, it can result in excessive boiler inlet temperatures at part-load conditions.

Variable power turbine nozzles also can be used to perform the variable geometry function. However, the use of modulating components in the high temperature turbine section raises gas turbine durability issues.

Development work is focused on a system that will enhance the performance of low emissions gas turbines at part load.

Controls Integration

A key element in achieving lower emissions in gas turbines is the further integration of the control system to more accurately control the combustion primary zone temperature (Tpz). Since the primary zone temperature is too high to measure directly, it has to be derived from a thermodynamic heat balance across the combustion system. The parameters used in this calculation are the compressor discharge temperature, the power turbine inlet temperature, the flow split between the combustor primary zone air and the total combustor air-flow, and the ratio of the power turbine inlet temperature to the first-stage turbine inlet temperature (T3).

Development work to date has led to the use of electronic actuators and variable pilot circuit controls. The long-term vision is to incorporate closed-loop controls with on-line, real-time sensing of NOx and CO levels. The shorter-term activity is focused on developing and improving the accuracy of the control algorithms necessary to control Tpz over the required load and ambient ranges.

Catalytic Combustion

The success of the first-generation lean-premixed combustion system has established that the technology is well-suited to meet NOx emissions levels as low as 25 ppmv. Development test data and production system performance suggest that lean-premixed combustion has the potential for even lower NOx levels. Lean-premixed combustion should be capable of meeting 15 ppmv NOx limits and perhaps limits as low as 9 ppmv. However, for a 9-ppmv NOx lean-premixed system, there may be significant load-range restrictions on the gas turbine, particularly if CO emissions limits are reduced from today's requirements. To achieve NOx emissions levels in the low, single-digit range and not compromise turbine

performance, it may be necessary to find an alternative to lean-premixed combustion. Catalytic combustion, or some yet to be recognized technology, will be necessary at the 3-ppmv NOx level, a level that is beyond the capabilities of lean-premixed combustion.

Concept Description

Catalytic combustion produces extremely low NOx levels by operating at very low flame temperatures of 1250 to 1350°C (2280 to 2460°F). Catalytic combustor flame temperatures are below levels that can be sustained in a lean-premixed combustor. The major element of this ultra-low NOx technology is a catalytic reactor that initiates and stabilizes the combustion process at conditions not normally sustainable through homogeneous (lean-premixed) combustion. Catalytic combustor components for gas turbine applications are illustrated in Figure 18.

The catalytic system has a number of features that are reminiscent of lean-premixed combustion and, in fact, a catalytic combustor can correctly be considered a catalytically stabilized, lean-premixed system. A typical catalytic combustor includes the following components: preburner, fuel injection/premixing section, catalytic reactor, homogeneous burn-out zone, part-load injector, and variable geometry system. All but the preburner and catalytic reactor are found in some form in the lean-premixed combustor.

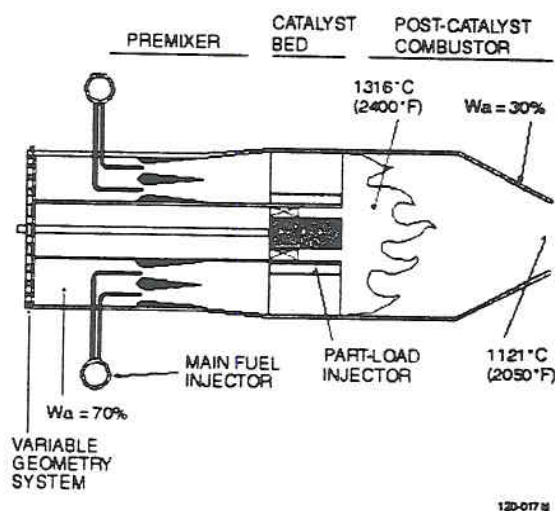


Figure 18. Catalytic Combustor Schematic

Although under development for nearly 20 years, catalytic combustion has yet to prove itself totally in a gas turbine environment. This is attributable to both unresolved technical issues and the lack of a significant market need. The state of catalytic combustion today is comparable to the status of lean-premixed combustion 10 years ago. Significant rig testing is ongoing, but the technology has not yet progressed to the long-term field-test stage. Significant technology milestones in the areas of catalyst and substrate durability, system integration, and controls remain to be achieved. Additionally, the economics of the technology need to be established as acceptable for the catalytic combustor to succeed in the marketplace.

SUMMARY

Despite the great success of the first-generation low emissions gas turbines in lowering NO_x emissions, manufacturers are dealing with the reality of even more stringent emissions regulations. Gas turbine manufacturers are working to improve the lean-premixed combustion systems used in current low emissions gas turbines and develop new and cleaner combustion technologies.

Improvements being advanced for lean-premixed combustion systems include advanced liner cooling technologies and more effective variable geometry systems. These technologies are well along in their development and are nearing or are already in the field-test stage. Full commercialization will depend upon a combination of technical success, market need, and economics.

Experience with lean-premixed systems over the last few years indicates that there is a practical lower NO_x limit associated with lean-premixed combustion. This limit appears to be in the 5-to-15 ppmv range. To achieve NO_x levels below this through low emissions combustion, gas turbine manufacturers are looking to catalytic combustion as the most likely candidate.

One issue affecting the development of advanced gas turbine combustion technology is the uncertainty in emissions levels that will be required in the future and a timeline for their implementation. Manufacturers are unable to focus development resources cost effectively

on well-established emissions targets, but must broaden development efforts to meet a range of emissions constraints. With limited resources available, this results in a slower pace of technology development.

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